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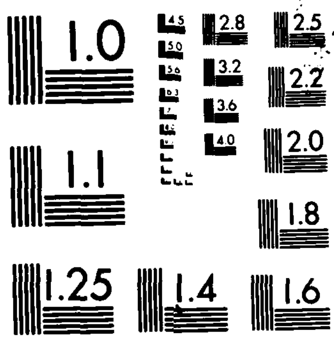

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A METHODOLOGY FOR SELECTION OF A SATELLITE SERVICING ARCHITECTURE

VOLUME II, FINAL REPORT

DESIGN STUDY

AFIT/GSE-85D

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GSE/ENY/85D —

(1)

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FOR

SELECTION OF A SATELLITE SERVICING ARCHITECTURE

VOLUME II, FINAL REPORT

DESIGN STUDY

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

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Graduate Systems Engineering

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Preface

The following report documents the design study of the Air Force Institute of Technology Graduate Systems Engineering Class of 1985. The report is in three volumes. The Executive Summary (Volume I) is a cursory review of the study and is meant to be self-contained. The Final Report (Volume II) and the Appendices (Volume III) are more detailed and should be read together for completeness. This study explains a two-phase methodology we developed to permit selection of an optimal military satellite servicing system. The work was conducted from December 1984 to December 1985. The original project concept and follow-on technical support was provided by the Rocket Propulsion Laboratory at Edwards AFB, California. Additional technical support and funding was provided by the Office for Manned Spaceflight (SD/YM) and the Office of Plans (SD/XR) at USAF Space Division, Los Angeles Air Force Station, California.

The faculty committee who assisted in this effort are:

Captain Stuart Kramer, Chairman

Dr. Curtis Spenny

Lt Col Mark M. Mekaru

Major Hugh C. Briggs

Their help in reading and helping us revise countless draft copies of this work is greatly appreciated.

A special measure of gratitude belongs to Major Dennis Clark for his help with the optimization program, and to Major Ken Feldman for his assistance with the value system. Our heartfelt thanks also goes to Mary Peltzer and Maggie Anderson, for their assistance with revisions of this document during the final hours.

We would also like to thank the following people for their assistance and guidance with different parts of this work. Without their help, parts of this effort would not have been possible: Major Don Brown, Mr. Robert Carlton, Colonel W.H. Crabtree, Colonel Gaylord Green, Colonel Donald G. Hard, Major James K. Hodge, Lt Colonel Janson, Mr. George Lemon, Lt Colonel Eric Sundberg, Lt Colonel Joseph Widhalm, Major G. V. Wimberly, Colonel William Wittress, and Colonel William F.H. Zersen.

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List of Symbols

Symbol	Description
Cr	Constraint Technique Constant
F	Feasible Region
Kg	Kilogram
Lu	Vector of Lower bounds of Control Variables
Lx	Vector of Lower bounds of State Variables
M	Maximal Eigenvalue
Mi	Initial total OSV mass
Mo	Final total OSV mass
Ms	Mass of OSV structure
P	Set of Elements Used in ISM
R	Relation
Sx	Feasible region in state space
Sz	Mapping feasible region into objective space
TOF	Time of flight for OSV mission
Ts	Synodic period
Tso	Period of the service orbit
Ttr	Period of the transfer orbit
Two	Period of the waiting orbit
U	Vector of Exogenous Variable
Ui	Exogenous Variable
Uu	Vector of Upper bounds on Control Variables
Ux	Vector of Upper bounds of State Variables

List of Symbols (Continued)

Symbol	Description
V( )	Value Function
V1	Velocity vector 1
V2	Velocity vector 2
Vpo	Velocity of parking orbit
Vtra	Velocity at apogee of transfer orbit
Vtrp	Velocity at perigee of transfer orbit
Vwoa	Velocity at apogee of waiting orbit
Wr	Weighted Technique Weight
X	Vector Of State Variables
Xi	ith State Variable
Z	Objective Function
Z	Vector of Performance Indicies
Zi	ith Performance Index
$\triangle$Va	Delta Velocity required at perigee
$\triangle$Vosv	Delta Velocity reequired for OSV mission
$\triangle$Vp	Delta Velocity required at perigee
$\triangle$Vresupply	Delta velocity required to travel from parking orbit to service orbit. enter service orbit. and return to parking orbit
$\angle$Vwo	Delta velocity required to get into and back out of waiting orbit
ge	Gravitational accelleration at surface of earth
pi	Element of Set P

List of Symbols (Continued)

Symbol	Description
ra	Radius at apogee of elliptical orbit
rearth	Normal radius of the earth
rp	Radius at perigee of elliptical orbit
rpo	Radius of parking orbit
rso	Radius of service orbit
tavgphase	Average time between OSV launch opportunities
tintersat	Travel time between satellites being serviced
tmaxphase	Maximum Time between OSV launch opportunities
tsatserv	Total time to service Y satellites (tservicing + tintersat)
tservicing	Time to service Y satellites

List of Abbreviations

Abbreviation	Description
AF	Air Force
CDC Cyber	Control Data Corp Cyber 175 Computer
DELIV	Delivered
DM	Decision Maker
DoD	Department of Defense
EMADAM	Extended Multi-Attribute Decision Analysis Model
EVA	Extravehicular Activity
FHG	Fixed High-G launch vehicle
FLG	Fixed Low-G launch vehicle
HLLV	Heavy Lift Launch Vehicle
HR	Hour
IC	Initial Cost
ICW	Initial Cost Weighting
ISM	Interpretive Structural Modeling
Isp	Specific Impulse of Fuel
KG	Kilogram
KTCN	Kuhn-Tucker Conditions for Noninteriority
Kg/Hr	Kilo Grams per Hour
Km	Kilometer
LEO	Low Earth Orbit
LG	Low-G launch vehicle
MADAM	Multi-Attribute Decision Analysis Model
MAUT	Multi Attribute Utility Theory

List of Abbreviations (Continued)

Abbreviation	Description
MAX	Maximize
MHG	Mobile High-G launch vehicle
MLG	Mobile Low-G launch vehicle
MMS	Multimission Modular Spacecraft
MOOT	Multiple Objective Optimization Theory
MPD	Mass of Payload Delivered
MPDW	Mass of Payload Delivered Weighting
MPI	Mutually Perferentially Independent
MWDI	Mutual Weak Difference Independent
NASA	National Aeronautics and Space Administraion
NDSS	Non-Dominated Solution Set
NSSDD-42	National Security Decision Directive 42
OC	Operating Cost
OCW	Overall Cost Weighting
OMV	Orbital Maneuvering Vehicle
OPCW	Operational Cost Weighting
OPS	Operating
OPW	Overall Performance Weighting
OSV	Ordital Servicing Vehicle
OTV	Orbital Transfer Vehicle
P/L	Payload
PERF	Performance

List of Abbreviations (Continued)

Abbreviation	Description
PI	Performance Index
PI	Performance Indicies
PPI	Pairwise Perferentially Independent
PROCES	Computer Program for Vector Optimization Problems
PrI	Preferentially Independent
R&D	Research and Development
REL	Reliability
RFP	Request For Proposal
RMS	Remote Manipulator System
RW	Reliability Weighting
SB	Space Base
SE	Systems Engineering
SSS	Satellite Servicing System
SUMT	Sequential Unconstrained Minimization Technique
SV	State Variable
SYS	System
TAV	Transatmospheric Vehicle
TC	Total Cost
USAF	United States Air Force
VOP	Vector Optimization Problem
WDI	Weak Difference Independent

Abstract

A two-phase methodology for selecting an optimal military satellite servicing system is developed using the systems engineering approach. This methodology is used to evaluate several alternative systems at varying levels of detail. The candidate systems are composed of low-G launchers, high-G launchers, orbital servicing vehicles, and space bases. An optimal realization is then derived for a system of low-G launchers and orbital servicing vehicles. In the first phase of the approach, vector optimization techniques are used to vary the states of a model to obtain a set of optimal solutions. The second phase embodies the decision maker's preferences in a value system to enable preference ranking of the optimal solutions in the non-dominated solution set. This methodology, as presented, can be applied to any complex problem with multiple conflicting objectives. It is designed for use by an engineering organization supporting a senior-level decision maker.

I. Introduction

1.1 Background

Satellites cost a great deal of money. Once placed in orbit, a failure of any number of subsystems can make the satellite useless. Until recently, the United States was unable to retrieve malfunctioning satellites, and the satellite was considered a total loss. But demonstrations using the Space Shuttle have proven that on-orbit servicing and repair of such satellites is now possible.

The concept of doing repair work or servicing in space is not new. In fact, it has been evolving steadily throughout the lifetime of the United States space program. Astronauts performed the first minor space repairs on their Gemini and Apollo spacecraft during the 1960s. Other astronauts performed even more dramatic repairs aboard the first American manned orbiting laboratory, Skylab.

Shortly after launch on May 14, 1973, telemetry data indicated problems with the yet unmanned Skylab. The sunshield had torn off creating temperatures inside the craft too high for human survival. Additionally, one of the two main solar arrays was missing and the other one was jammed in a near-closed position.

By the time the first Skylab crew launched on May 25, the National Aeronautics and Space Administration (NASA) had developed tools and procedures for the crew to use in

repairing Skylab. During the six months that the lab was manned, the three crews accomplished many unplanned maintenance tasks, including cleaning a telescope, hammering loose a stuck electric relay, rotating a jammed filter with a screwdriver, and repairing a rate gyro. Including the planned servicing activities -- the changing of film magazines -- a total of ten extravehicular activities (EVA) were made totalling 82.5 man-hours. Thus the Skylab experience provided additional proof that repair of space assets on-orbit is not only possible, but that man can routinely accomplish it.

The success of the Skylab repairs was not just due to luck and quick thinking. Large tool kits were aboard the lab, and crews had completed extensive pre-mission ground training in simulators. In short, extensive planning and preparation had made it possible for NASA to deal successfully with the emergency repairs.

Ideally, planning for space repairs should be part of the satellite design, as was done with the Solar Maximum Mission satellite (Solar Max). Solar Max is the first of a series, known as the multimission modular spacecraft (MMS), designed to be serviced by the Space Shuttle. The satellite is modular in design for quick access and removal of components. It is equipped with a grapple fixture that allows the Remote Manipulator System (RMS) of the Shuttle (also known as Canadarm) to snare Solar Max and place it in the

bay of the Shuttle. Due directly to this design forethought, the Shuttle was able to successfully retrieve and repair Solar Max when several failures disabled the satellite. This type of preparation through satellite design shows great promise for future servicing missions by the shuttle. Space World magazine reported that:

> A 1975 study by Rockwell International .... estimated that almost $3 billion could be saved by using extravehicular activity (EVA) to deploy, maintain, or repair satellites....(Dooling, 1982).

However, the Shuttle was not designed to be primarily a repair platform or servicing system. Its main function is still as a transportation system between Earth and low earth orbit (LEO).

Designing serviceable satellites does depend on the type of system doing the servicing, as was the case with Solar Max and the Canadarm system. Conversely, the design of the servicing system is also dependent on the system to be serviced. Both considerations are important if satellite servicing is to become routine.

The commitment of this nation to achieve and maintain a position of leadership in space transportation was established by the enactment of the National Space Policy of 1982. President Reagan emphasized this commitment when he directed NASA on 25 January 1984 to develop a permanently manned space station within a decade.

NASA and the Air Force have both made commitments to make their satellites serviceable. As a result of the United States Air Force Spacecraft Maintenance Policy Review Study (Dept. of AF, 1984) the Undersecretary of the Air Force for Research and Development directed that:

> The Air Force policy is to ensure that spacecraft maintenance options are considered in requirements definition, acquisition program management, and contractual documentation for those satellite programs wherein these options might be reasonably implemented. The Air Force should actively examine the utility of spacecraft maintenance options (particularly preventative maintenance, refueling and repair) and avoid, wherever practicable, design actions which would appear to preclude on-orbit maintenance later in the spacecraft life cycle (Aldridge, 1984).

In May 1985, the USAF Space Division issued a Request For Proposal (RFP) for contractors to develop alternatives for a Space Transportation Architecture. As stated in the statement of work portion of the RFP:

> The primary objectives of this study are to (1) determine the overall space transportation architecture(s) and transportation systems that can most cost effectively perform future DOD and NASA missions projected for the 1995 through 2010 time period, (2) identify the enabling technologies required for future space transportation systems and prepare an integrated plan to develop these technologies, and (3) refine the mid-1990's transportation system concept(s), and prepare preliminary system specifications and special engineering plans for refined concept(s) to facilitate the start of the Validation Phase (Dept. of AF, 1985).

It is to a request such as this one that this design project is addressed. Specifically, a methodology is developed and demonstrated for selecting a military

satellite servicing architecture from among many candidates.

There are two approaches which may be used to make decisions such as this: the traditional engineering approach or the systems engineering approach. In the traditional approach, although large amounts of detailed information are gathered, there is a tendency not to evaluate requirements and tradeoffs. The systems engineering approach ensures that this is done.

The traditional approach to the selection or design process begins with establishing a set of minimum system requirements. Candidate systems that do not at least meet these requirements are eliminated. When one or more systems are found that satisfy the minimum requirements, an arbitrary selection of one of them is normally made. Design work is then started on that system's subcomponents. Since other systems may exceed the minimum requirements, but were not examined, this approach usually results in selection of a system that is less than optimal in cost or performance. Typically, the majority of the design work in the traditional approach is spent on designing each little piece of the system. Late in the design, the little pieces are forced to interface, and only then are integration problems discovered. In addition, cost overruns and design changes on each little piece affect the total system's efficiency, which is only as good as the least efficient piece in the system. Because the traditional engineering approach does

not usually include tradeoffs that analyze changes to parts of the total system, the system discrepancies are not discovered until late in the design process. In conclusion, the traditional engineering approach can be an inefficient method for solving complex problems, and often does not identify the optimal solution.

In contrast, the systems engineering approach presents an efficient methodology for designing today's complex systems. Requirements are used along with the constraints of the design project to define all acceptable candidate systems. Those systems that exceed the requirements while satisfying the constraints are candidates for being optimal solutions. The individual candidates are then optimized from a total systems viewpoint versus a piece-by-piece optimization. This permits identification of the design requirements for the individual pieces after an optimal workable system design is obtained. The systems engineering approach is also an iterative process that improves on the total design at each iteration. The result is a set of candidate solutions, optimized to achieve the objective in the problem statement.

The objectives of this study, its scope, and assumptions are outlined below.

1.2 Problem Statement

Develop and demonstrate a methodology for selecting an optimal military satellite servicing system (SSS).

1.3 Scope

A systems engineering approach is used to develop a two-phase methodology for selecting an optimal military satellite servicing system. The methodology is designed for use by an engineering organization supporting a senior-level decision maker. Consequently, the problem objectives and measures of effectiveness are developed from a senior military decision maker's viewpoint. Candidate architectures consist of a means to get mass to orbit (launch vehicle system), and a means to service satellites on-orbit (service vehicle system). Several candidate architectures are evaluated, with an optimal realization derived for a system of low-G launchers combined with orbital servicing vehicles. No attempt is made to evaluate the economic benefits such a system could provide nor are specific design requirements for satellite serviceability addressed.

1.4 Assumptions

This study is based on the following assumptions. Further assumptions of narrower scope will be presented in each section of this report where they apply.

1. A justified need for servicing satellites exists.

2. The satellites to be serviced have been designed to be accessible, and the satellite requirements will drive the design of the servicing system.

3. The decision maker using this methodology is at the Department of Defense (DOD) level of Government and will view a system's effectiveness from a military perspective.

4. The satellite servicing system will be purchased and operated by the Department of Defense.

1.5 Deliverables

This effort has resulted in the following:

1. A two-phase methodology is explained that is particularly useful for solving complex problems with multiple conflicting objectives. This methodology is applied specifically to the problem of determining the best type of servicing architecture to develop for servicing military satellites on-orbit.

2. Three candidate architectures are modeled mathematically; the equations and explanations are included in Appendices D-F for these systems:

a) Low-G launch system with orbital servicing vehicles (LG-OSV)

b) Low-G and fixed high-G launch systems with orbital servicing vehicles (LG-FHG-OSV)

c) Low-G and fixed high-G launch systems with orbital servicing vehicles and space bases (LG-FHG-OSV-SB)

The entire methodology is carried out for the LG-OSV architecture, with the resulting optimal realizations included in this study. The same procedures should be used for the other two alternatives, but time constraints prevented their inclusion in this effort.

3. A discussion of the orbital mechanics and accompanying equations used for designing the servicing system models are included in Appendix G.

4. A listing for a Fortran-based computer program for calculating change in velocity (delta v) and time of flight for an OSV traveling between a resupply orbit and a servicing orbit is included in Appendix H. The servicing orbit is determined by the altitude and inclination of the satellites. The program is interactive and allows the user to specify the altitude and inclination of the resupply orbit, the number of satellites to be serviced in the orbit during that mission, and the maximum number of waiting orbits. There is also an option that calculates propulsion fuel mass used.

1.6 Sequence of Presentation

Chapter II describes the two-phase methodology that is used in this study. The steps of the methodology, as they relate to selecting an optimal satellite servicing architecture, are described in detail in chapters three through six. Chapter III contains a development of the value system, part of the second phase of the methodology. Chapter IV

describes the generation of alternative solutions through synthesis and modeling. In Chapter V, the generated alternative systems are optimized and evaluated. Chapter VI discusses decision making based on these optimal solutions. Conclusions and recommendations are in Chapter VII.

II. Methodology

2.1 Introduction

2.1.1 Overview. The systems engineering (SE) approach has evolved as man has attempted to solve large complex problems related to modern technology. The SE methodology is not a rigid procedure for solving problems, but rather a set of tools and techniques tied together by a distinct approach. In general, the SE methodology provides a framework that helps one identify the important parameters and boundaries surrounding an issue, aids in developing and modeling solutions, emphasizes optimizing these solutions, and then provides a mechanism for selecting the most appropriate answer from this set of solutions.

The approach begins with defining the problem and identifying an overall objective. Often, especially in large complex problems, this objective is somewhat vague and provides no indication of a direction to proceed to achieve it. In these cases it is helpful to decompose the problem or overall objective into manageable subobjectives (or functional areas), that provide more detail about the problem under study. Understanding each of the subobjectives allows a broader understanding of the whole problem, and consequently encourages better solutions. Each subobjective can be thought of as a piece of a jig-saw puzzle. Each piece by itself yields only a small clue, yet it is a necessary part

to complete the puzzle. By identifying the shape or structure of each of the pieces, it is easier to understand how each little piece must fit together to form the total picture.

As an example, if the overall objective is to design an economical air superiority fighter aircraft, one might define subobjectives to give more detail about what is needed. One subobjective might be "must have optimal performance" and another might be "minimize total cost." Satisfying the subobjectives satisfies the overall objective. Likewise, these two subobjectives could be broken down even further. For example, performance might depend on speed capability desired, and weapons delivery systems needed. Cost could depend on initial system purchase cost and operating costs. At the objective level with the highest degree of detail, one can usually determine what measures of effectiveness are needed to show the degree of attainment of each objective. These measures of effectiveness, or performance indices (PI), can then be used to rate how well a candidate solution achieves the overall objective.

Some subobjectives will have physically measurable characteristics, while others will not. In the example above, the engine thrust and aerodynamic drag in the fighter design relate to the speed capability objective. However, the desire for the fighter to be a politically stabilizing

force in the international community, would be an objective that cannot be physically measured. Both are still valid objectives, and both can be satisfied using the SE approach.

In a complex problem, subobjectives often conflict with each other. Complete satisfaction of one subobjective may result in less than maximum satisfaction of another. One of the greatest advantages of the SE approach is that it can be used on exactly this type of problem.

The basis of the systems engineering approach is to optimize the overall objective by simultaneously optimizing the performance indices. This differs from the traditional engineering approach, which has a tendency to optimize the subcomponents independently and then fit the pieces together. The traditional approach may work well for problems where the solution has been well-established by past experience. But in a complicated problem where the analysis procedure, models, or objectives are not well-established, the traditional approach can result in a lot of wasted effort on an ill-formed problem. Imagine three groups trying to design a different part of an aircraft independently, with the objectives of having a strong structure, a rugged landing gear, and a powerful propulsion system. If the three groups did not coordinate their designs to achieve a workable aircraft, the exaggerated results in Figure 2.1 could conceivably occur.

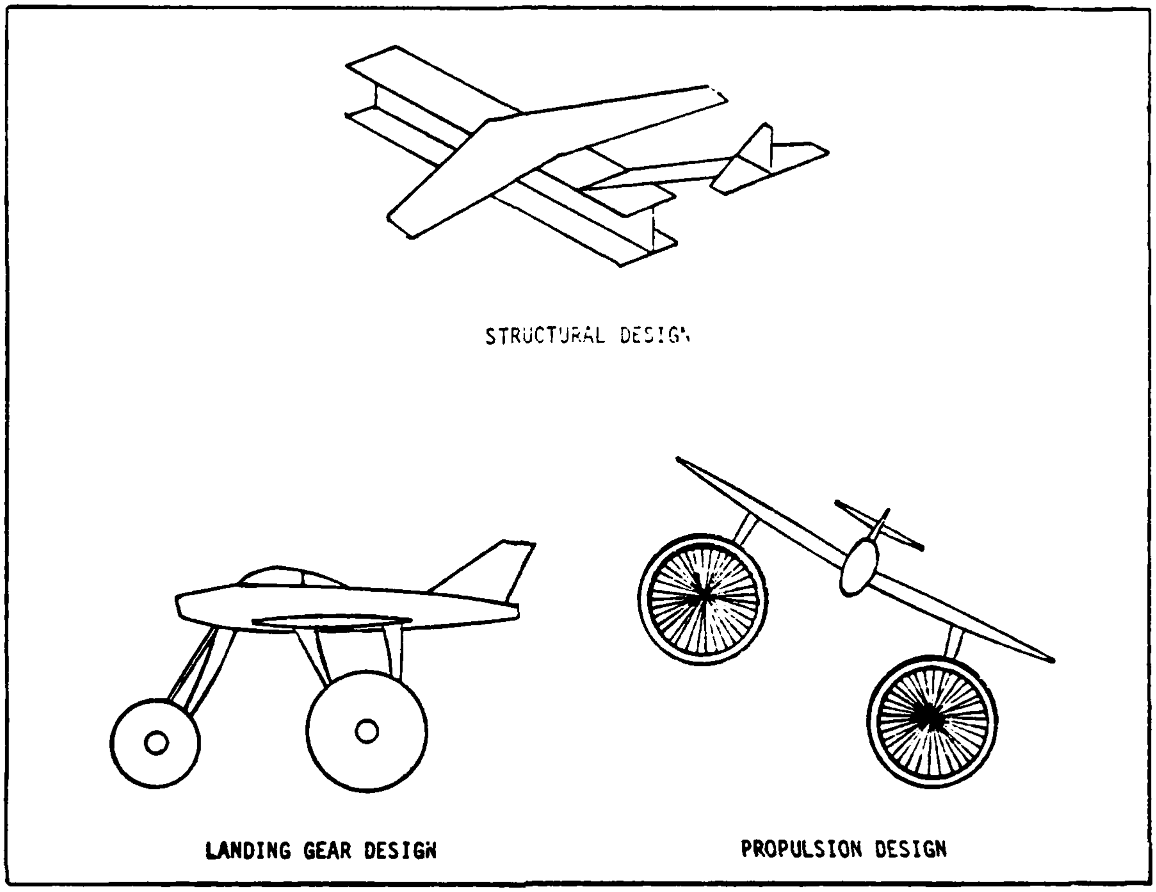

Figure 2.1 Design of an Aircraft by Subcomponents

By doing a simultaneous optimization, all of the subcomponents are permitted to achieve their maximum potential in relation to the other subcomponents in the entire system. The overall objective is not lost and the interaction of the parts is maintained. The result is a set of optimal solutions from which a decision maker can then make his selection based on his own preferences.

One of the primary characteristics of the SE approach is its iterative nature. In the first attempt to solve the

problem, one seeks a very crude solution as is represented by the first peak of the curve in Figure 2.2.

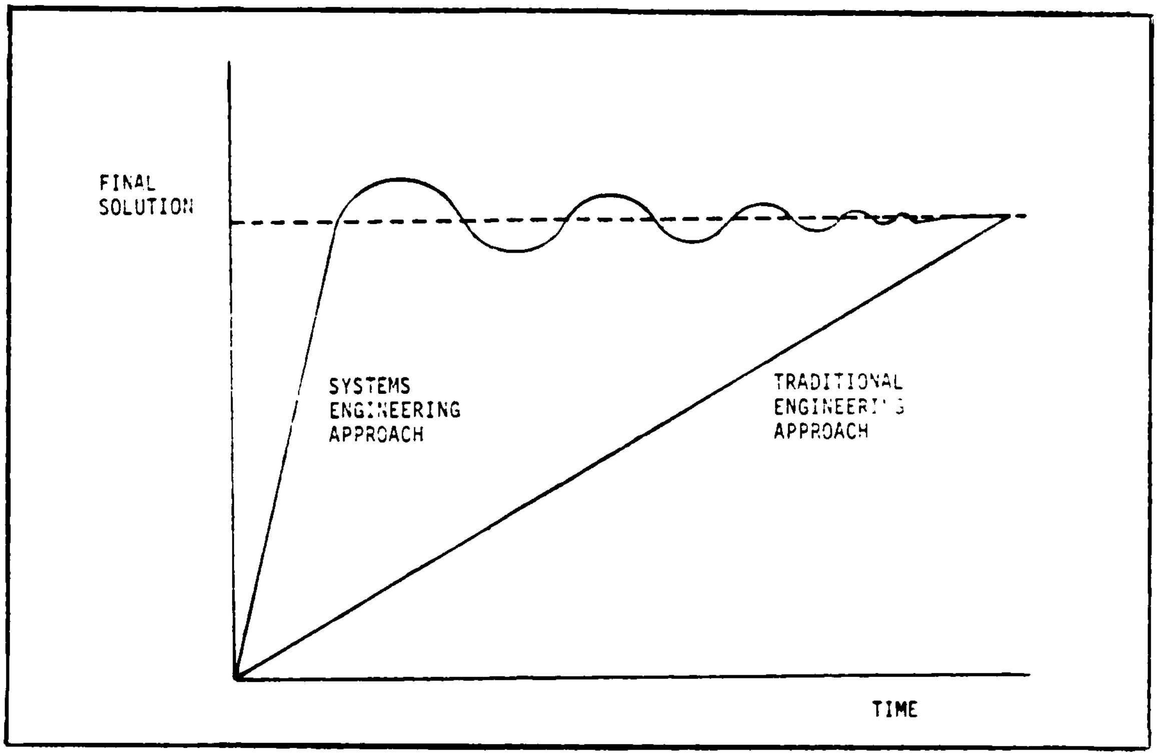

Figure 2.2 SE Approach vs. Traditional Engineering Approach

The steps of the methodology are repeated over and over, with lessons learned early in the design process from preliminary solutions used to find better solutions in the next iteration. As more is learned through each subsequent attempt, the iterations converge to the final solution. This is in contrast to the traditional engineering approach, which tends to seek a straight line solution over time. It does not approach an answer until late in the design when the subcomponents are fit together. In the SE approach, mistakes and potential dead ends are recognized early, thus

saving manpower and money -- an obvious advantage over the traditional approach.

In general the SE approach can be applied to any problem. The approach is flexible enough to allow tailoring of specific steps in the methodology to best fit the problem being examined. Many authors have described this methodology using steps that fit the phases of a system's life. Perhaps the most general description is given by Hall (Hall,1969). He uses a three-dimensional framework with a system's life phases on one axis, the systems engineering steps on a second axis, and knowledge from various disciplines on the third axis. Two of these dimensions can be displayed in an activity matrix as shown in Figure 2.3.

Steps of the fine structure / Logic → / Phases of the coarse structure / Time ↓	Problem definition	Value system design	System synthesis	Systems analysis	Rank (optimize) alternatives	Decision making	Planning for action
Program planning							
Project planning							
System development							
Production							
Distribution							
Operations							
Retirement							

Figure 2.3 Hall Activity Matrix for Systems Engineering

The seven steps of systems engineering are carried out in an iterative fashion. This means that it is possible to go back and refine or improve the results of any lower-numbered step as a consequence of the results of any higher-numbered step (Sage, 1977:3). These seven steps are repeated for each of the seven system life phases. The methodology described in this paper will be an adaptation of Hall's approach. Other authors describe variations that may be appropriate for a particular problem (Chestnut, 1965; DeNeufville and Stafford, 1971; Hill, 1970; Sage, 1977; Tribus, 1969:394).

The SE approach is particularly well-suited to solving complex problems (Sage, 1977:1-3). Determining the best combination of systems to use for on-orbit servicing of satellites is just such a problem.

2.1.2 Two-Phase Approach. Typically in problems with multiple, conflicting objectives, the design or decision process can be separated into two phases. The first phase involves problem definition, system synthesis and modeling, optimization, and model sensitivity analysis (Clark and DeWispelare, 1985). The end product of this first phase is a set of solutions with the characteristic that no one solution in the set can be considered a better solution than any other, from an engineering viewpoint. All solutions can be considered to be "equally optimal." As an example, consider two candidate solutions, A and B, from this optimal set.

System A may outperform system B in the measure of one performance index, but system B will outperform system A in the measure of a different PI. This set of solutions is thus appropriately termed a "nondominated solution set" or "NDSS."

The second phase of the approach provides a mechanism for including the preferences or "values" of the decision maker (DM). Inclusion of the decision maker's "value system" in the solution process enables the analyst to create a ranking of the optimal solutions in the NDSS based on the decision maker's own preferences. This ranked listing of solutions is an efficient method for communicating results to a busy decision maker. The second phase of the methodology includes designing a "value system", ranking the solutions in the NDSS, and selection of a solution by the DM for implementation.

While the methodology is separated into two distinct phases, they may overlap in time. Typically, design of the value system is begun immediately after problem definition.

It is advantageous to use this two-phase approach because it separates the costly and normally time-intensive first phase from the preference-laden and volatile second phase (Clark and DeWispelare, 1985:84). Decision maker values do sometimes change, due to either external events or simply reevaluation by the DM of his preferences. However,

as long as the essential elements of the problem do not change, the first phase does not have to be reaccomplished, regardless of how the decision maker's preferences change.

2.1.3 Basic Steps of the Methodology. The basic steps of the SE approach, using this two-phase methodology, are applied in this study to the problem of selecting a satellite servicing architecture. Below is a sequential overview of the steps in the approach. The sections in this chapter will describe these steps individually.

Application of the methodology involves problem definition, design of a value system, synthesis and modeling of alternative solutions, analysis and validation of those solutions, alternatives ranking and selection of an appropriate solution, and planning for future actions. This same sequence of steps is performed over and over until one is satisfied that the process has converged to a solution.

The first step in the approach is problem definition. This stage involves research to improve understanding of the true problem, since the problem cannot be defined properly until the real problem is determined. Next, a value system is designed that expresses the preferences of the decision maker. The value system identifies important objectives, and allows direct systematic mathematical analysis of the decision maker's preferences. Again, the value system is part of the second phase of the SE approach, and is indepen-

dent of the first phase. It is suggested that the value system be designed at this point of the methodology. This ensures that the performance indices derived in the second phase by the decision maker are the same performance indices used during the modeling in the first phase. Although arbitrary performance measures may be used in the model, this coordination step can save a great deal of effort later in the solution process. Alternative solutions to the problem are identified or created in the third step. These alternative or candidate solutions are then modeled to permit direct analysis. From the analysis, one determines how well the candidate solutions meet the objectives established in the problem definition step. This analysis includes optimization of the alternatives, and validation of the system models and solutions. This information is then used to rank the alternatives from most to least desirable, using the decision maker's preferences. The final step in the SE approach is planning for action. This step will vary, from iterating through all the steps again to gain more detail and information for improving the current solution, to implementing the final solution.

2.2 Problem Definition Step

Problem definition is the key initial step in the SE approach. In this step the framework for the rest of the process is set. Considerable care must be taken to ensure that the "real" problem is identified and addressed. It is

also important to determine not only the overall problem or goal, but also the decision situation that brought about consideration of this problem. Other important items requiring identification during the problem definition step include: the "actors" involved in the problem, what factors can and cannot be controlled, and the likely system inputs and desired outputs.

Flexibility is necessary during this step, since knowledge gained during later iterations should be used to modify the problem definition when appropriate. The first attempt at the problem definition is usually rather abstract; necessary details can be added on later iterations. Once a problem definition is formulated, the analyst should ask the decision maker to confirm that it is indeed the problem of interest.

2.2.1. Decision Situation and Actors. It is important to fully understand the factors that created the issue under consideration in order to set the problem boundaries. Interviews with the "actors" involved in the problem and thorough research will enable one to establish this framework. The actors are the individuals who are affected by the problem, and the individual(s) responsible for solving or implementing a solution. Sometimes these groups are identical. Identification of the actors also identifies the decison maker(s) for the issue. The decision maker is "an individual or a group of individuals who directly or

indirectly furnishes the final value judgement that may be used to rank available alternatives, so that the 'best' choice can be identified ... ... whenever final value judgements need to be made concerning the 'goodness' or 'badness' of a given choice, they are to be made by the decision maker" (Chankong and Haimes, 1983:8).

2.2.2 <u>Controllable Factors and System Inputs/Outputs</u>. Once the decision situation and actors have been identified, the system parameters must be analyzed. This involves determining the constraints of the problem and identifying the alterables, or problem factors that can be controlled. It is also necessary to isolate and relate the relevant variables involved in the problem.

Hall suggests one technique for determining the system inputs and outputs by imagining the total system as a "black box" (Hall, 1962:99). Inputs to the system are listed arbitrarily on one side of the box and outputs on the other. Following this "free-thought" process, the analyst attempts to match the correct inputs with the corresponding outputs. If this is not yet possible, the black box should be broken into subsystems, and the process repeated.

Another method for determining the important components in the problem definition is the "who-what-when-where-why" approach. By answering each of the "w" questions, one can normally get a feel for the scope of the problem and the

variables involved.

2.3 Value System Design Step

After properly defining the problem in the first step, the analyst will be able to state the overall objective of the problem. The overall objective is needed to design a value system for the decision maker. As described earlier, design of the value system, although part of the second phase of the methodology, is typically begun after the problem definition.

The design of the value system in a complex problem usually begins with the creation of a hierarchy tree of objectives. The decision situation or overall objective is placed at the top of the tree. Those objectives whose successful accomplishment would result in reaching the overall objective are placed at the second level of the tree. This is continued until a level is reached where the attainment of an objective can be directly measured. These measures of performance, or performance indices, indicate the relative level of achievement of the objectives. There is not a unique hierarchy of objectives for any problem. Consequently, if the analyst creates the hierarchy of objectives for the decision maker, it is recommended that the decision maker approve and agree with the problem as it is structured.

The level of objective attainment measured by each

performance index at the bottom of the hierarchy tree will be different for each candidate solution in the NDSS. Consequently, every decision maker will prefer one solution over another, based either on established policies, or on personal bias from his own experiences. The purpose of the value system is to capture those preferences for inclusion in the solution process. The value system is an organized method for discriminating among a set of otherwise equally optimal solutions (from an engineering point-of-view).

In a complex problem, there will be many different ways to measure the degree of attainment of the objectives using different performance indices. Consequently, it is recommended that the performance indices at the bottom of the hierarchy tree be used as the measures of performance for the candidate solutions in the NDSS. This is necessary before any modeling has begun to ensure that the model outputs the desired measures. Otherwise considerable effort may be required later to convert the NDSS values to the performance index values needed for the hierarchy tree. After the objective tree and performance index measures have been established, the preferences of the decision maker do not have any impact on the solution process until the first phase of the methodology has been completed. The remainder of the value system design can be accomplished independently from the first phase steps.

The analyst next investigates the preferences the

decision maker has for different objectives and for the units that measure those objectives. Every decision maker will have a different utility or degree of satisfaction associated with the measure used for each performance index. If the measure of a performance index for initial cost is in dollars, a decision maker may have different utilities associated with various quantities of dollars. For instance, he may prefer a system costing $100 million versus a system costing $10 billion. This degree of satisfaction can be represented by a utility curve. This curve maps the range of measures of a performance index to the value that DM associates with each measure. A decision maker may also have different preferences associated with each objective in the hierarchy tree. He may desire to emphasize the accomplishment of one objective over the accomplishment of another. The analyst determines these types of preferences by having the decision maker do preference comparisons for the objectives on each level of the tree. This process allows a decision maker to rank objectives two-at-a-time, enabling him to give a greater weight or emphasis to those objectives that he feels are important. Chapter III describes these methods and how they are implemented.

2.4 Alternatives Generation Step (System Synthesis and Modeling)

Identification or creation of alternative solutions is the next step in the SE approach. Primarily this involves

determining different ways to attain each objective, describing each alternative approach, and measuring the degree of attainment of each approach. Often this is termed system synthesis (Sage, 1977:73). Research accomplished during the problem definition phase will undoubtedly identify some potential candidate solutions. However, it is desired to include as many potential solutions as possible, to preclude overlooking a viable candidate. Brainstorming is an excellent technique for a first attempt at generating solutions. (Sage, 1977:167-176) describes the merits of using brainstorming, brainwriting, and Delphi techniques for generation of ideas in a group. The primary goal is to identify as many different ways as possible to accomplish the objectives defined in the problem definition. Since this methodology uses an iterative approach and optimizes the candidates that are generated, unworkable ideas will quickly fall out.

Once a set of candidates has been generated, some method of describing and analyzing these alternatives must be used. Typically, the different system alternatives are described in terms of a model. In its most general definition a model is "a representation of a system which can be used as an explanatory device, an analysis tool, a design assessor, or even a crystal ball." (Pritsker, 1984)

There are various types of models, including physical (iconic), graphical (visual), and mathematical models

(Pritsker, 1984:2). Mathematical models can be conveniently viewed as either dynamic (functions of time) or static (independent of time). Dynamic models are used to replicate system characteristics as they change with elapsing time. This is more commonly referred to as simulation. Static models represent the interrelations between characteristics of a system. Usually these relationships do not depend on elapsing time, or the effect of time is small enough to be negligible. In this study, static models are referred to as analytical models.

The type of model one selects is dependent on such factors as budget, time availability, accuracy needed, flexibility desired, and control over environmental influences. For instance, a physical model might be used to gather initial aerodynamic data for a new airfoil design. However, due to its expense, a physical model would be totally inappropriate to analyze the impact of changes to an interstate transportation network. Instead, a computer simulation model could be built which would allow easy operation and wide flexibility at low cost.

In addition, a model should describe and differentiate between proposed systems while predicting the performance of each. The form of the model must be such that analysis techniques can be used to answer predetermined questions. In this study, one such question is, "What are the trade-offs that can be made between the number and types of

subsystems and what effect does this have on the overall system performance?" Physical and graphical models are inadequate to answer this question. Physical models are too expensive to build for every possible alternative satellite servicing system (SSS), and graphical models do not allow any flexibility in controlling the environment or in varying the model attributes. Mathematical (analytical or simulation) models, however, do have the flexibility and cost effectiveness that is needed for this study.

The system model should provide system performances that are measured in terms familiar to the decision maker, so that he can understand the merits of each system. A large list of possible SSS performance measures is presented in section 3.2.3. Both the analytical and simulation type models can be used to measure these attributes. For this study, analytical models were chosen so that the static or time-independent behavior of the solution could be investigated.

Mathematical optimization techniques, using digital computers to manipulate analytical models, provide an efficient way to generate sets of optimal system realizations. For the problem of selecting the best satellite servicing architecture, multiple objective optimization theory (MOOT) techniques can be used. Chapter V contains a detailed explanation of MOOT techniques applied to this problem. MOOT techniques are designed to analyze problems with

conflicting objectives. If these objectives did not conflict, the problem solution would reduce to a scalar optimization problem yielding a single optimal answer. In selecting a SSS the performance measures are indeed conflicting. For instance, to achieve a desired increase in mass delivered to orbit, an undesirable increase in system costs occurs.

To use MOOT techniques, the analytical model equations are cast into statespace form. In this form, the characteristics that describe the system are called state variables, and the measures of system performance are called performance indices. A more detailed description of the statespace form is presented in section 4.3.1.

2.5 Systems Analysis Step

During this step of the methodology, the candidate system models are analyzed to yield optimal engineering solutions. This analysis consists of two parts: generation of the members of the NDSS, and validation of those results. MOOT techniques are used to generate the non-dominated solutions for this study. The resultant NDSS is then analyzed to determine the validity of the models and the results.

For the problem of selecting an optimal satellite servicing system, multiple objective optimization theory techniques were found to be the most helpful tool for analysis. Using MOOT, an optimizer algorithm, PROCES, is used to

recursively vary the states of the model over the design space to produce a trial solution. This trial solution is then compared against the members in the non-dominated solution set. If the trial solution is not dominated by another solution, it is added to the NDSS. Eventually a set of non-dominated solutions is created that covers the design space for each modeled system.

Once an NDSS is generated, the validity of the solutions must be confirmed. Sensitivity analysis is one of the most powerful methods used for checking the validity of the system models and solutions. By analyzing the solutions in the NDSS, the analyst can determine potential problems with the model or the optimizer algorithm. Identified problems are corrected and the entire process is then repeated. This iterative approach permits early identification of flaws in the model or in the optimizer, enabling better solutions with each iteration. However, there will always be a certain amount of error or uncertainty associated with the solutions, since a model cannot perfectly duplicate the real world.

During the validation step, the analyst looks not only for the parameters to which the solutions are sensitive, but also for the solutions which are sensitive to changes in the parameters. Conversely, he also looks for robust solutions, or solutions which are relatively insensitive to changes. The decision maker can then use this information to select a

solution that is appropriate for his needs. In Chapter V, the process of generating an NDSS and validating the model and solution set are demonstrated.

2.6 Solution Ranking and Selection Step (Decision making)

This step, along with the design of the value system, embodies the second phase of the SE approach. Alternative system descriptions have been modeled, the models have been validated and analyzed, and a set of nondominated "equally-optimal" solutions have been found. Now it is the responsibility of the decision maker to select one solution for implementation.

Each solution in the NDSS represents a different system realization (i.e. size, shape, number) for a particular overall system architecture. Consider as a candidate architecture a system consisting of some combination of space shuttles, space bases, and orbital servicing vehicles. Each solution in the NDSS represents a specific description of that architecture, and is an optimal realization in that it cannot outperform any of the other realizations in all areas. However, with all other performances being equal, one system description may cost more for operations, or one may have higher reliability. Consequently, a decision maker will likely have more preference for one solution in the set over the others. The choice of solution belongs to the decision maker. The SE approach, then, allows a supporting engineer-

ing organization to provide not the solution, but a choice of solutions for consideration by the decision maker. Selection of a solution is described by DeNeufville and Stafford (1971:12) to be

> "by definition, not a technical problem alone. The analysts' role is precisely that of helping the decision process by removing as many of the technical uncertainties as possible ... systems analysis is fundamentally an attempt to define issues and alternatives for the decision maker and then to provide him with the information relevant to his choice."

The value system is simply a mechanism that captures the decision maker's preferences for incorporation into the solution process. The decision maker's utility for the performance measures is multiplied by the weighting preferences of the objectives in the hierarchy tree and summed. This yields a single figure of merit which embodies the DM's preference for each solution in the NDSS. The different solutions in the NDSS can then be rank-ordered by their associated figures of merit. This is described in more detail and demonstrated in Chapter III. It is also helpful for a decision maker to know how sensitive the solution ranking is to changes in his preference weightings. A robust solution which may not have been ranked the highest may be a more advantageous selection, especially if there is uncertainty in some of the system parameters. Sensitivity analysis of an NDSS is described in Chapter VI.

2.7 Planning for Action Step

Planning for action is directly tied in with decision making. In this step the analyst examines the progress taking place in the solution process, and decides what refinements are needed and to what degree. Since the same seven steps are repeated over and over, the action taken here may vary with each iteration. Early in the design, the action taken is usually to continue with greater detail through a new iteration, incorporating the information gathered and lessons learned. The new iteration should correct areas of uncertainty that were uncovered, while continually working towards a better answer. After the process has converged to a satisfactory set of solutions, the analyst may use this step to plan how to communicate the results to the decision maker(s). Once the decision maker has the results, his decisions will likely drive future actions on the project, be that implementation or shelving of the project.

2.8 Summary

This chapter has explained in general terms the methodology that is used in this study. The methodology is divided into two phases, to separate the engineering design portion from the preference-laden and therefore volatile second phase.

The next chapter describes why the second phase is a necessary part of a methodology for solving a complex

problem. It covers the theory and application for developing a value system for any decision maker.

The remaining chapters explain the detailed application of the rest of the methodology as applied to the problem of selecting an optimal satellite servicing system.

III. Value System Development

3.1 Overview

The problem of selecting a satellite servicing architecture is multi-faceted and involves many tradeoffs among the problem objectives. Because some of these tradeoffs depend on the preferences of the decision maker(s) (DM) involved, it is necessary to include the decision maker's values (preferences) in the solution process. The mechanism that does this is termed the value system.

These preferences are not normally used until a set of candidate solutions is generated, which is why the value system is the second phase of the systems engineering (SE) approach. However, to facilitate a better understanding of the role of a value system in the methodology, this chapter precedes the discussion of most of the steps in the first phase.

Every decision maker has a unique value system, which is simply a formal mathematical representation of his preferences. If certain axioms are met, a mapping of those preferences to a value scale can be accomplished. Multi-attribute utility theory (MAUT) is the theoretical framework that is used to create this mapping. This chapter will lead the reader from a development of MAUT through the calculation of figures of merit for the solutions in the non-dominated solution set (NDSS).

The first section in this chapter presents an introduction to the value system, and develops the theoretical framework of multi-attribute utility theory. An analyst must understand the appropriate theory applicable to his problem in order to begin to design the value system. Section 3.2 describes the hierarchy approach, which is a useful way to break a problem into meaningful parts for analysis. Section 3.3 presents a technique for capturing a decision maker's preferences to be used for weighting a problem's objectives. Section 3.4 investigates the utility or "value" that a decision maker associates with the units of measure for each performance index. In section 3.5, the hierarchy approach, weighted objectives, and performance "values" are all combined to determine a scalar figure of merit. This figure of merit represents the preference a decision maker has for a particular solution in the non-dominated solution set (NDSS). The solutions in the NDSS may then be rank-ordered by their figures of merit to yield a set of optimal solutions listed in preferred order (for a particular DM). Ranking of the optimal candidate solutions is demonstrated in Chapter VI, Decision Making. Section 3.6 presents a two page-summary that recaps the basic ideas of this chapter.

3.1.1 <u>Introduction to the Value System</u>. A multi-objective problem like this one can be characterized by a feasible region F that satisfies the problem constraints, and by an overall objective function, Z, that can be partitioned into

measurable ojective functions, z_i, where

$$Z = f(Z_1(X), Z_2(X), \ldots, Z_n(X)) \tag{3.1}$$

(Goicoechea et al, 1982:19). For this study, Z represents the overall objective of selecting an appropriate satellite servicing system. This overall objective is a function of many other objectives, such as the desire to minimize costs and maximize performance. The vector $\underline{X}$ is a set of state variables that uniquely describes each candidate solution. One way of physically representing this overall objective, Z, as a function of its subobjectives, Z_i, is in the form of a "tree," as shown in Figure 3.1. (The concept of a hierarchy tree will be covered in greater detail in Section 3.2.) Each level of the tree completely describes the overall objective, but at a different level of detail. At the lowest level of the tree structure, the objectives can be quantifiably measured in some way by a set of descriptors. These descriptors are termed "attributes," or for the purposes of this study, "performance indices" (PI). The terms attributes and performance indices will be used interchangeably in this study. The overall objective, Z, can then be written as a function of these performance indices, $Z_i(\underline{X})$, as shown in equation 3.1. In other words, the accomplishment of the overall objective can be completely described in terms of the measures of the performance indices (which represent the measure of accomplishment of the objectives on the bottom level of the tree).

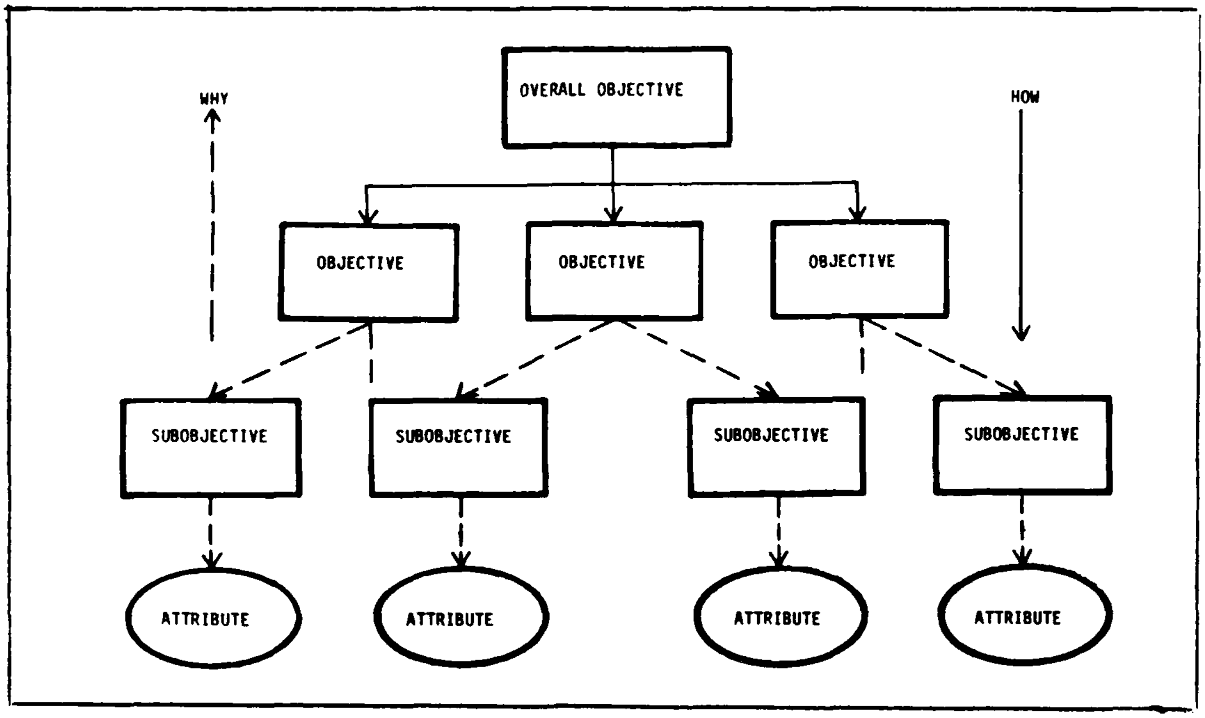

Figure 3.1 Hierarchy of Objectives (Chankong and Haimes, 1983:9)

Each candidate solution, which is described by the $\underline{X}$ state variables, will have an associated level of accomplishment for each of these performance indices, $Z_i(X)$. In a sense, the levels of the set of performance indices describes each alternative solution. Usually, calculation of these performance indices is by straight-forward deterministic methods. Sometimes, however, the information related to a particular index is unknown or uncertain. In these cases, a probability distribution is used to represent the performance index. If none of the PI describing the solution involves uncertainty, the alternative solution is termed a "certain alternative." If there is uncertainty associated with the measure of any of the PI, the associated solution is termed an "uncertain alternative."

In single-objective problems it is possible to find a single optimal solution. However, for a multi-objective problem, the solution is usually in the form of a set of non-dominated solutions (NDSS) which is a subset of the feasible region. The main characteristic of the non-dominated set of solutions is that for each solution outside this set (but still within the feasible region), there is a non-dominated solution for which all performance indices are unchanged or improved and at least one which is strictly improved (Goicoechea et al, 1982:19). A more formal mathematical description of the NDSS may be found in Goicoechea. See the analysis part of this report, Section V, for a detailed discussion of the NDSS.

The set of non-dominated solutions is determined during the first phase of the SE approach without considering the preferences of the decision maker. Consequently the NDSS is independent of DM preferences, and the first phase of the approach need not be reaccomplished if the DM preferences change. In order to select a best or most acceptable solution for a particular DM, out of this set of optimal solutions, it is necessary to include the value judgements of that decision maker. This is an important point. Every alternative in the set of non-dominated solutions is, from an engineering viewpoint, an acceptable "optimal" solution. Because each decision maker may prefer certain performance indices over others, he will probably prefer one solution in

the NDSS over the others. These preferences (based on the decision maker's intuition and experience) are described by his value structure. By incorporating the decision maker's value structure into the problem, the alternatives in the NDSS may be rank-ordered to determine which is the best-compromise solution for his purposes. In the "Theory of the Displaced Ideal", Zeleny points out:

> If one obtains an accurate measurement of the net attractiveness (or utility) of each available alternative, one can predict with reasonable accuracy that a person will choose the alternative which is 'most attractive.' So, the problem of prediction of choice becomes the technical problem of measurement and mechanical search. Furthermore, if the alternatives are complex and multi-attributed, then the measurement of utility could be too difficult to be practical. The real question concerns the process by which the decision maker structures the problem, creates and evaluates the alternatives, identifies relevant criteria, adjusts their priorities and processes information....It is important to realize that whenever we face a single aggregate measure, there is no decision making involved. The decision is implicit in the measurement and it is made by the search....It is only when facing multiple attributes, objectives, criteria, functions, etc., that we can talk about decision making and its theory (Zeleny, 1975:157).

3.1.2 Discussion of Utility Theory. Involved in any decision making process is the task of constructing a preference order, so that alternatives may be ranked and the final choice may be selected (Chankong and Haimes, 1983:62). Utility theory assumes that an individual can choose among alternatives and pick the one choice from which he derives the most satisfaction. Relative to the vector of objectives, it is assumed that all information pertaining to the various

levels of the objectives can be captured by an individual's utility function. In essence, an individual's utility function is a formal, mathematical representation of his preference structure (Goicoechea et al, 1982:26).

An individual's preferences must satisfy certain conditions in order to be representable by a utility function. The number of conditions varies from four to six depending on how they are presented (Sage, 1977:329). Goicoechea demonstrates these conditions in the form of the four axioms below, as derived by Markowitz. If an individual conforms to these axioms, a utility function can be constructed that will express his preferences for outcomes involving certainty or uncertainty (Goicoechea et al, 1982:26). Only the first two axioms must be satisfied for alternatives involving certainty. The axioms are (Markowitz, 1959):

1. For two alternatives, A_1 and A_2, one of the following must be true: the individual prefers A_1 to A_2, prefers A_2 to A_1, or is indifferent between them.

2. The individual's evaluation of alternatives is transitive: if he prefers A_1 to A_2, and A_2 to A_3, then he prefers A_1 to A_3.

3. Assume that A_1 is preferred to A_2, and A_2 to A_3, then there exists some probability p, $0<p<1$, that the individual is indifferent between outcome A_2 with certainty, or getting A_1 with probability p and A_3 with probability (1-p). In other words, there exists a certainty equivalent to any gamble.

4 Assuming an individual is indifferent between two choices, A_1 and A_2, and if A_3 is any third alternative, then he will be indifferent between the following two gambles: Gamble 1 offers a probability p of receiving A_1 and a probability (1-p) of receiving A_3, and Gamble 2 offers a probability

p of receiving A_2 and a probability (1-p) of receiving A_3.

Once the utility function is determined, it can be used to order the set of non-dominated solutions. The non-dominated solution which yields the highest utility will be the best-compromise solution for the problem for that decision maker (Goicoechea et al, 1982:27).

3.1.2.1 Value Functions and Utility Functions. All problems involving decision theory can be separated into one of four types as shown in Figure 3.2. Problems with "certain alternatives" are described by value theory (also called deterministic utility theory) and the associated utilities are represented by value functions. To emphasize the differences, problems involving uncertainty or random occurrences (uncertain alternatives) are described by utility theory (also called expected utility theory) and are represented by utility functions. Figure 3.3 shows the methodology appropriate to each type problem. All future references to general multi-attribute utility theory (value theory and utility theory) will use the term MAUT (multi-attribute utility theory) to include cases under both certainty and uncertainty. The more descriptive individual terminology will be used when appropriate. While there are many commonalities in the basis for MAUT under certainty and uncertainty, the main differences occur in the manner in which the preferences are solicited to determine the value

OUTCOME UNDER	SINGLE ATTRIBUTE	MULTIPLE ATTRIBUTE
CERTAINTY	Type I	Type III
UNCERTAINTY	Type II	Type IV

Figure 3.2 Decision Problem Dichotomy (DeWispelare and Stimpson, 1983:2)

OUTCOME UNDER	SINGLE ATTRIBUTE	MULTIPLE ATTRIBUTE
CERTAINTY	Scalar Optimization	Multi-Attribute Value Theory
UNCERTAINTY	Single Attribute Utility Theory	Multi-Attribute Utility Theory

Figure 3.3 Decision Problem Methodology (Feldman and Rowell, 1985)

function or utility function. Since this report details a methodology involving multi-attribute decision theory with certain alternatives, multi-attribute value theory and determination of value functions will be discussed primarily.

There are two important functional forms of a multi-attribute utility function (certainty or uncertainty) in MAUT.

One is the additive form described by

$$U(\underline{X}) = \sum_{i=1}^{n} K_i U_i(X_i) \qquad (3.2)$$

where

$U(\underline{X})$ is normalized: $0 \leq U(\underline{X}) \leq 1$

U_i is the single attribute function of X_i normalized: $0 \leq U_i(X_i) \leq 1$

the scaling constants K_i are positive and sum to 1.

An example of a three-attribute additive value function is the following:

$$V(X_1, X_2, X_3) = K_1 V_1(X_1) + K_2 V_2(X_2) + K_3 V_3(X_3) \qquad (3.3)$$

The other important functional form is the multiplicative form described by

$$U(\underline{X}) = \sum_{i=1}^{n} K_i U_i(X_i) + K \sum_{i=1}^{n} \sum_{j>1}^{n} K_i K_j U_i(X_i) U_j(X_j)$$
$$+ K^2 \sum_{i=1}^{n} \sum_{j>1}^{n} \sum_{l>j}^{n} K_i K_j K l U_i(X_i) U_j(X_j) U l(X l)$$
$$+ \ldots + K^{n-1} \prod_{i=1}^{n} K_i U(X_i) \qquad (3.4)$$

where

$U(\underline{X})$ is normalized: $0 \leq U(X) \leq 1$

$U_i(X_i)$ is normalized

K_i is positive and less than 1

K, the coupling coefficient solves $1 + K = \prod_{i=1}^{n} (1 + KK_i)$

An example of a of multiplicative value function is the following:

$$
\begin{aligned}
V(X_1, X_2, X_3) = {} & K_1 V_1(X_1) + K_2 V_2(X_2) + K_3 V_3(X_3) \\
& + KK_1 K_2 V_1(X_1) V_2(X_2) + KK_1 K_3 V_1(X_1) V_3(X_3) \\
& + KK_2 K_3 V_2(X_2) V_3(X_3) \\
& + K^2 K_{12} K_3 V_1(X_1) V_2(X_2) V_3(X_3) \qquad (3.5)
\end{aligned}
$$

(Feldman and Rowell, 1985; Goicoechea et al, 1982:28,124)

3.1.2.2 Independence Conditions. The appropriate type of utility function to use is dependent not only on the problem to be solved, but also on the determination by the decision maker that the problem objectives satisfy certain independence conditions. These conditions will now be discussed.

The pair of attributes (X_1, X_2) out of an n-tuple of attributes $(X_1, X_2, \ldots, X_n)$ is preferentially independent (PrI)* of its complementary attributes $(X_3, \ldots, X_n)$ if preferences among (X_1, X_2) with the complement fixed do not depend on the level at which $(X_3, \ldots, X_n)$ are fixed.

As an example suppose that three subobjectives for selecting a satellite servicing system are

SCC - satisfies congressional concerns

MA - accomplishes the mission

ULR - utilizes limited resources optimally

The value tradeoffs between satisfying congressional concerns and accomplishing the mission may not depend on how well the system utilizes the limited resources that are available. On a value scale of 0 to 1, assume ULR is set at a value of .2. If the preference between SCC and MA does not change when ULR is changed to .7 or any other value, then {SCC,MA} is preferentially independent of {ULR}.

---

* In the literature, "preferentially independent" is commonly abbreviated "PI." In this thesis, PI represents performance index. To avoid reader confusion, PrI is used for preferentially independent.

If each pair of attributes is preferentially independent of its complement, the attributes are pairwise preferentially independent (PPI).

In our example above, the same type of comparisons would be done for each possible combination of pairs. If in addition to {SCC,MA} being preferentially independent of {ULR} (or {SCC,MA} PrI {ULR}), if {MA,ULR} PrI {SCC}, and {SCC,ULR} PrI {MA}, then these attributes are pairwise preferentially independent.

The attributes $X_1,\ldots,X_n$ are mutually preferentially independent (MPI) if every subset Y of these attributes is preferentially independent of its complementary set (Keeney and Raiffa, 1976:111).

For three or more attributes, pairwise preferential independence is equivalent to mutual preferential independence (Keeney and Raiffa, 1976:114). MPI is a necessary and sufficient condition for an additive value function (Feldman and Rowell, 1985). The necessary and sufficient condition for use of a multiplicative value function is satisfaction of mutual weak difference independence (MWDI).

The attributes are MWDI if for any one of the attributes, X_i, it can be shown:

1. X_i is weak difference independent (WDI) of its complementary set $\{X_1,\ldots,X_{i-1},X_{i+1},\ldots,X_n\}$

If each pair of attributes is preferentially independent of its complement, the attributes are <u>pairwise preferentially independent</u> (PPI).

In our example above, the same type of comparisons would be done for each possible combination of pairs. If in addition to {SCC,MA} being preferentially independent of {ULR} (or {SCC,MA} PrI {ULR}), if {MA,ULR} PrI {SCC}, and {SCC,ULR} PrI {MA}, then these attributes are pairwise preferentially independent.

The attributes $X_1,\ldots,X_n$ are <u>mutually preferentially independent</u> (MPI) if every subset Y of these attributes is preferentially independent of its complementary set (Keeney and Raiffa, 1976:111).

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The attributes are MWDI if for any one of the attributes, X_i, it can be shown:

1. X_i is <u>weak difference independent</u> (WDI) of its complementary set $\{X_1,\ldots,X_{i-1},X_{i+1},\ldots,X_n\}$

2. $\{X_i, X_j\}$ is preferentially independent of its complementary set $\{X_1, \ldots, X_{i-1}, X_{i+1}, \ldots, X_{j-1}, X_{j+1}, \ldots, X_n\}$, where i is not equal to j.

The test for weak difference independence will be explained shortly. MWDI requires that a total of n tests be performed -- the first test need be done only once for only one attribute, and the second test need be done n-1 times with that same attribute in combination with all other attributes (Feldman and Rowell, 1985). Preferential independence, used in the second test, was demonstrated in an example earlier.

The first test, satisfaction of weak difference independence, can be best explained in an example. Assume there are n attributes. Take one attribute out of the set, say X_1, and set its complementary set $\{X_2, \ldots, X_n\}$ to its lowest level. Assume six points (including the endpoints) are known on the value curve for X_1, as in Figure 3.4.

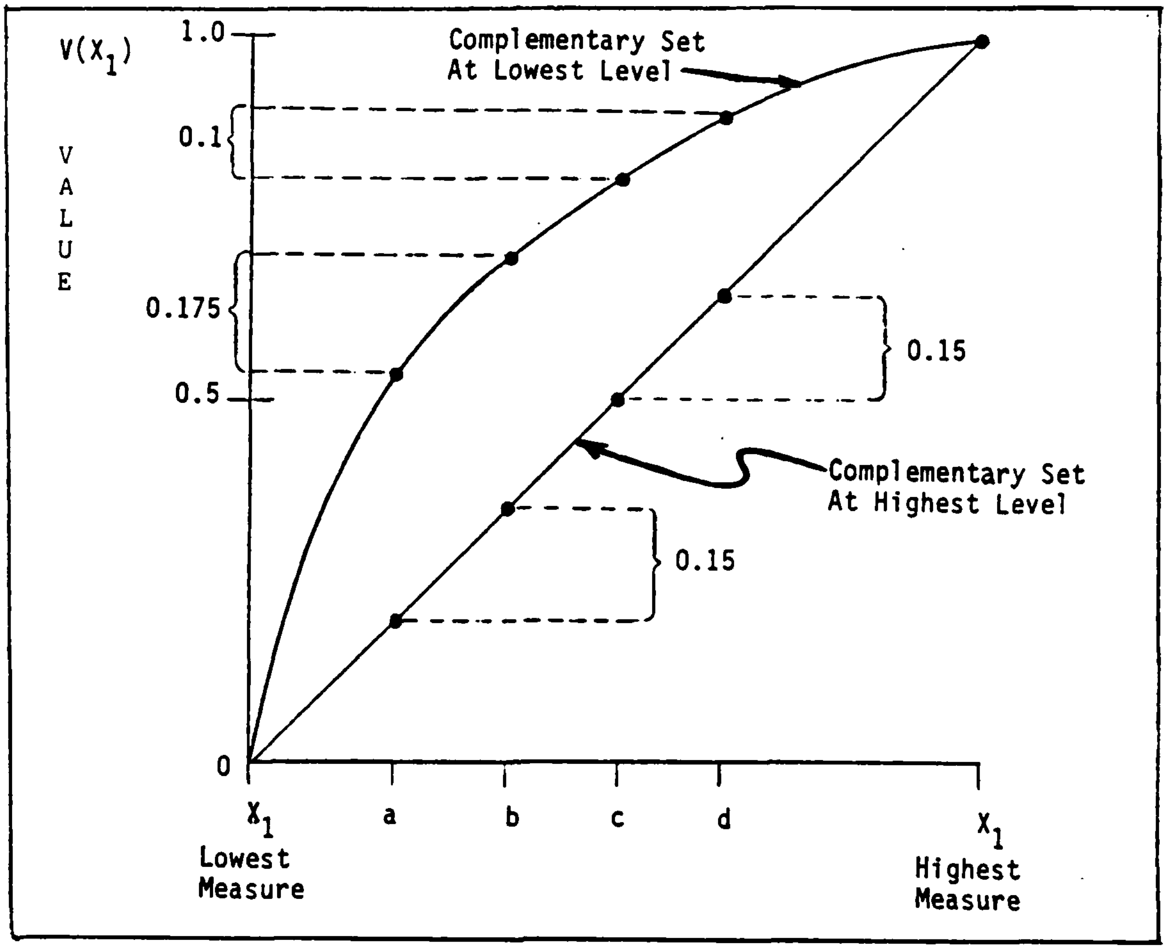

Figure 3.4 WDI Test (Feldman and Rowell, 1985)

There is a positive value difference relationship established between (V(b)-V(a)) and (V(d)-V(c)), of .175 and .1, respectively. If the complementary set is then changed to its highest level, the resulting value curve for the same four points should be examined. If (V(b)-V(a)) is still greater than or equal to (V(d)-V(c)), then X1 is WDI of its complementary set, and the first test is satisfied (Feldman and Rowell, 1985). This positive value difference relationship must hold for any arbitrary four points selected. In other words, the relationship in the above example also

holds for the differences (V(c)-V(a)) greater than or equal to (V(d)-V(b)). In essence, the two value curves conditioned by different levels of the complementary set, must be very similar to each other. The interested reader is referred to (Chankong and Haimes, 1983:81-88) for additional discussion of MWDI. Utility theory (uncertainty) involves similar independence conditions and the interested reader will find an extensive discussion of them in (Chankong and Haimes, 1983: 88-109), (Keeney and Raiffa, 1976:Ch 6), or (Sage, 1977:328-346).

The value system design described in this paper uses an additive value structure with "certain" alternatives. Satisfaction of mutual preferential independence for the objectives used in this study is demonstrated in Appendix A. Satisfying MPI guarantees that an additive value function can be used. The remainder of this paper will be based on this additive structure using value functions. In summary, this additive value structure can be represented by equation 3.2 or

$$V(\underline{X}) = K_1V_1(X_1) + K_2V_2(X_2) + \ldots + K_nV_n(X_n) \qquad (3.6)$$

3.1.2.3 Value Function Shape. Once the appropriate structure (additive or multiplicative) is determined, the shape of the value function curve must be identified for each performance index. In other words, the actual function that represents each $V_{i(X_i)}$ in equation 3.6 must be found. There

are a number of methods available in the literature for determining the shape of the value function, including the lock-step procedure, midvalue splitting technique (Keeney and Raiffa, 1976:94-100), and the analytic hierarchy process (Kamenetsky, 1982:702-712). There are also a number of good software packages available to aid in this task. The computer program MADAM (Multi-Attribute Decision Analysis Model) is one such program that may be used to define the shape of the single-attribute value functions, $V_i(X_i)$. MADAM is written in FORTRAN V and is an interactive program designed to test for the necessary and sufficient conditions for an additive value function and to evaluate the resulting value function if these conditions are met (Dewispelare and Stimpson, 1983). An extended version of MADAM (EMADAM) is currently implemented on the CYBER 175 computer system at the Air Force Institute of Technology (Dewispelare, 1983). This extended version includes the incorporation of utility concepts to allow analysis of problems involving uncertainty. Computer code for this program is available by contacting Captain Stuart Kramer, Department of Aeronautics and Astronautics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, 45433.

MADAM uses the midvalue splitting technique to define points on the single-attribute value curve and then allows one of five functions to be fit to the points generated. Manuals for MADAM are available through the Defense Technol-

ogy Information Center (Stimpson, 1983). Using the midvalue splitting technique to determine the shape of the value function curve will be demonstrated in detail in section 3.4.2.

3.2 Hierarchy of Objectives, Hierarchy Approach (Chankong and Haimes, 1983; DeWispelare, 1983; Saaty, 1980)

The previous section provided the necessary theoretical framework for determining a decision maker's preferences. In order to use this framework it is necessary to create an ordering of the set of problem objectives. This section will explain how this hierarchy of objectives is constructed and used in the value system.

3.2.1 Objectives. An objective is a condition about the desired state of the system being considered, giving the general direction to which effort will be exerted. In the multiple-attribute decision problem, there will be several conditions expressing the decision maker's desired state of the system. An objective is not the same as a goal; a goal is a specific level of some performance measure which is or is not achieved. An objective designates no specific level, but indicates direction. Objectives are directions toward which the system should be proceeding and they are standards against which the quality or performance of an alternative may be evaluated.

A well-defined set of objectives often exhibits a

hierarchial structure, as illustrated in Figure 3.1. Moving up through the hierarchy, the subobjectives should indicate the means to an end; the end is indicated by a parent or overall objective. A result of this is that the movement up the hierarchy has a natural stopping point at the parent or overall objective. This objective should give the overall reason for the decision maker's interest in the problem, and often, it is too vague for operational purposes. Moving down through the hierarchy's levels, the objectives at the lower level are more specific and more operational than those in the higher level. These lower level objectives are viewed as the means to achieving the higher ends represented by the parent objective. The movement down through the hierarchy has no well defined stopping point. It is up to the decision maker to determine the extent of available resources and take a practical attitude towards the amount of detail desired.

Breaking a parent objective into subobjectives is called "specification". Specification allows division of the objectives into subobjectives with increasing amounts of detail. The more detailed subobjectives are designed to encompass all aspects of the parent objective. At each stage of specification, the group of subobjectives should be tested to decide whether or not some of the subobjectives may be insignificant relative to the other. If any are found to be insignificant, they should be deleted.

3.2.2 Attributes. To use the hierarchial structure, a set of attributes is assigned to each objective in the lowest level. The attribute set provides a means of measuring the degree to which the lowest-level objectives (and therefore, indirectly, all the objectives) are satisfied. Each attribute should be comprehensive. A comprehensive attribute clearly shows the decision maker how well its associated objective is achieved. The lowest-level objectives show the degree of detail to be used in the decision analysis, and the attribute set contains at least one attribute to measure each of the lowest-level objectives. There is no unique attribute set for a given objective hierarchy.

There are three kinds of attributes: normal, proxy, and direct preference measures. Normal attributes are those attributes which directly measure their associated objectives. Proxy attributes reflect the degree to which the associated objectives are met, but do not directly measure the objectives. The direct preference measure attribute indicates on a subjective scale of worth the degree to which an objective is met. This scale is dependent upon the decision makers preferences. The most desirable attribute is the normal attribute, since it involves direct measurement of the level of accomplishment of the objective. The least desirable attribute is the direct preference measure, because of the subjective measures involved. All efforts should be made by the decision maker to insure that each

attribute does measure what was intended.

There are several desirable properties for the set of attributes as a whole. The attribute set should be operational, complete, decomposable, non-redundant, and minimal. An operational attribute is descriptive, easy to use, and has significance to the decision maker. A set of attributes can be termed complete if the decision maker is satisfied that there are enough attributes to measure the level of accomplishment of the overall objective. Completeness may be indicated when the lowest level of objectives in the hierarchy includes all areas of concern. The attribute set should also be decomposable, implying that subsets of the whole attribute set may be examined separately from the others, to check for the different kinds of independence described in section 3.1.2.2. A non-redundant attribute does not allow double-counting of consequences. For instance, if two attributes used to describe the quality of a nation's health are "deaths due to cancer" and "male deaths", one attribute would be double-counting the males who died from cancer. Having a minimal set means that the attribute set is kept as small as possible, bounded by all of the preceding properties.

3.2.3 Hierarchy Approach. There are several advantages to using the hierarchial approach. The hierarchial structure as shown in figure 3.1 enables the analyst to see how changes in the priorities of the upper levels influence the

priorities of the lower levels. Hierarchies also offer detailed information on the structure and function of a system in the lower levels, while providing an overview of the objectives and their purposes in the upper levels. The objectives of systems developed hierarchially evolve much more efficiently than those developed in other ways. The process of leading the analyst gradually through greater amounts of detail in objective development, helps eliminate misconceptions of subcomponent relations that are likely to occur if the final level of detail is derived directly. When used, hierarchies enable calculation of how well a system meets the objectives presented. The degree to which a system meets all objectives generally changes very little when objectives within the hierarchy are varied slightly. Also, for a well structured hierarchy, minimal additions cause minimal influence in the degree that a system meets all objectives.

To determine a hierarchy, Saaty (Saaty, 1980:p14) recommends using a brainstorming session to generate all possible elements. Once these elements have been generated they can be functionally located at various levels as appropriate. The functional representation of a system in hierarchial form is not unique to a particular system, but depends upon an individual's concept of the problem situation.

Sage uses interpretive structural modeling or ISM to

help determine the appropriate structural relationships between elements of a system (Sage, 1977:Ch 4). Consequently, ISM could be used to establish the appropriate structure for a hierarchy tree. A discussion of ISM may be found in Section 4.2.3.1.

A hierarchy of objectives developed for this study is shown in Figure 3.5. It consists of three levels. The overall objective, found at Level 1, is to select the best satellite servicing system. This objective is accomplished when the Level 2 objectives (satisfying political concerns, minimizing cost, and maximizing performance) are accomplished. Similarly the Level 2 objectives depend on the Level 3 objectives.

After discussions with decision makers at the USAF Space Division (Green, 1985; Lemon, 1985; Sundberg, 1985; Wimberly, 1985; Wittress, 1985; Zersen, 1985) a more comprehensive hierarchy of objectives was developed. This new hierarchy, consisting of six levels and 40 objectives and subobjectives, is shown in Figure 3.6. A detailed description of this hierarchy may be found in Appendix B.

To facilitate demonstration of this methodology using easily measurable attributes, the simplified hierarchy in Figure 3.7 was developed. Although this is an overly simplified set of objectives for this problem, it will be much easier for the reader to follow application of this metho-

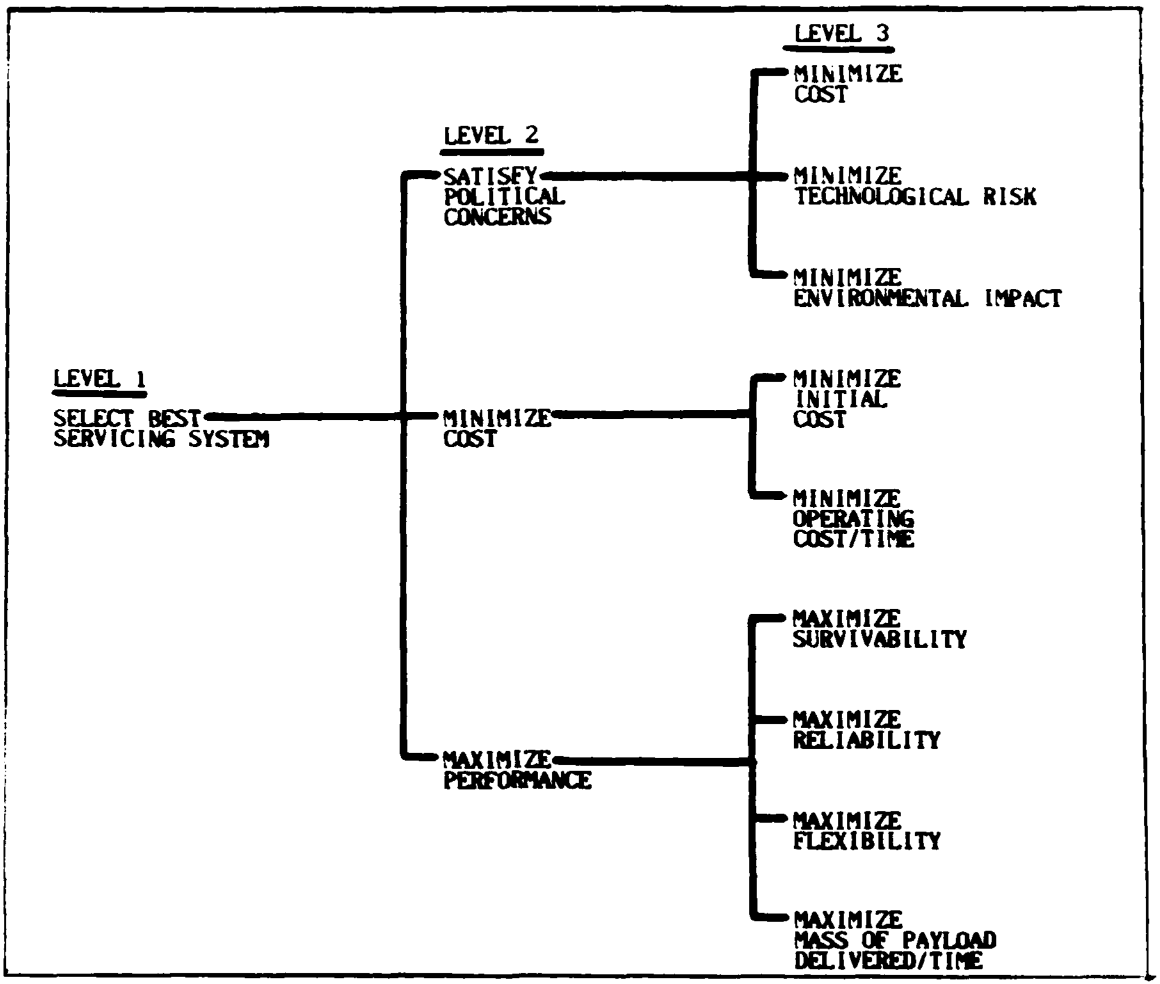

Figure 3.5 Hierarchy of Objectives

dology using it. This same methodology may be applied to the larger hierarchy.

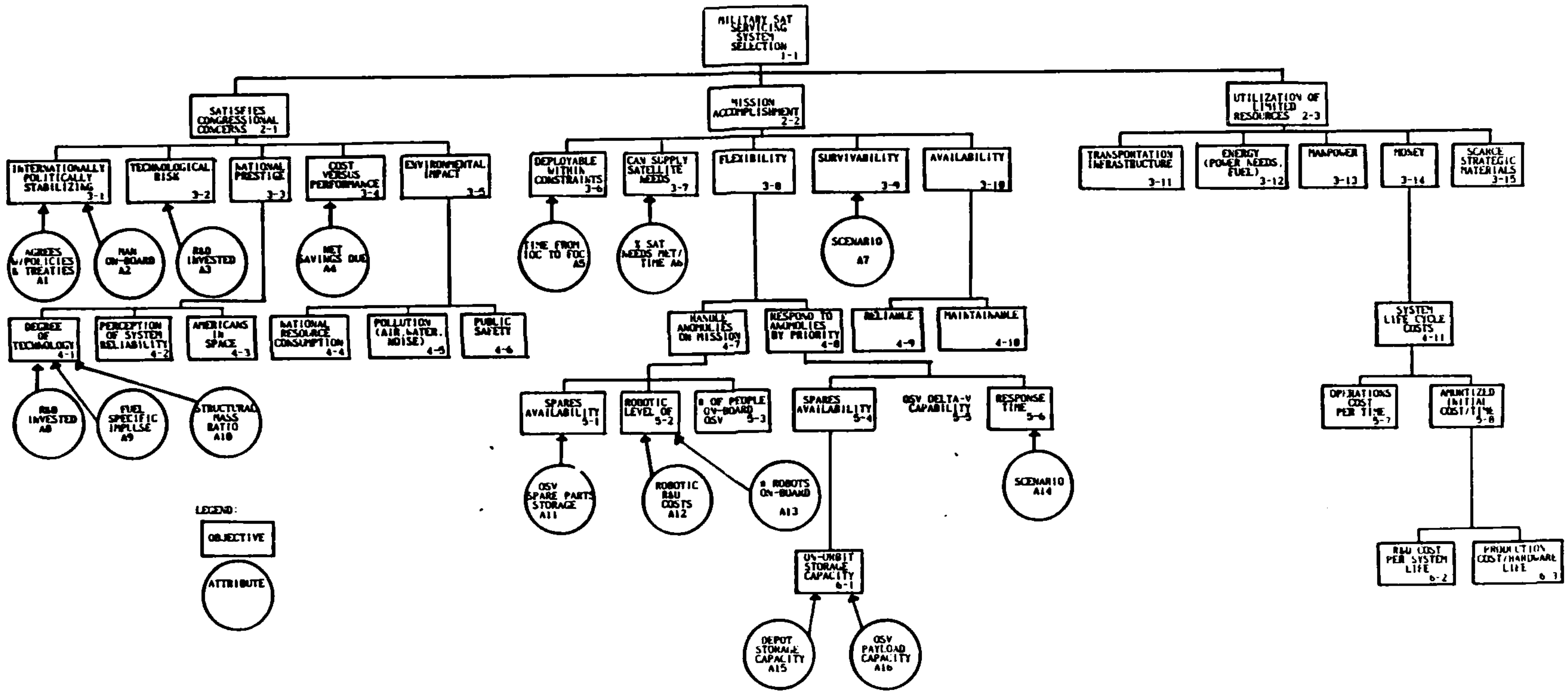

Figure 3.6 Comprehensive Hierarchy of Objectives

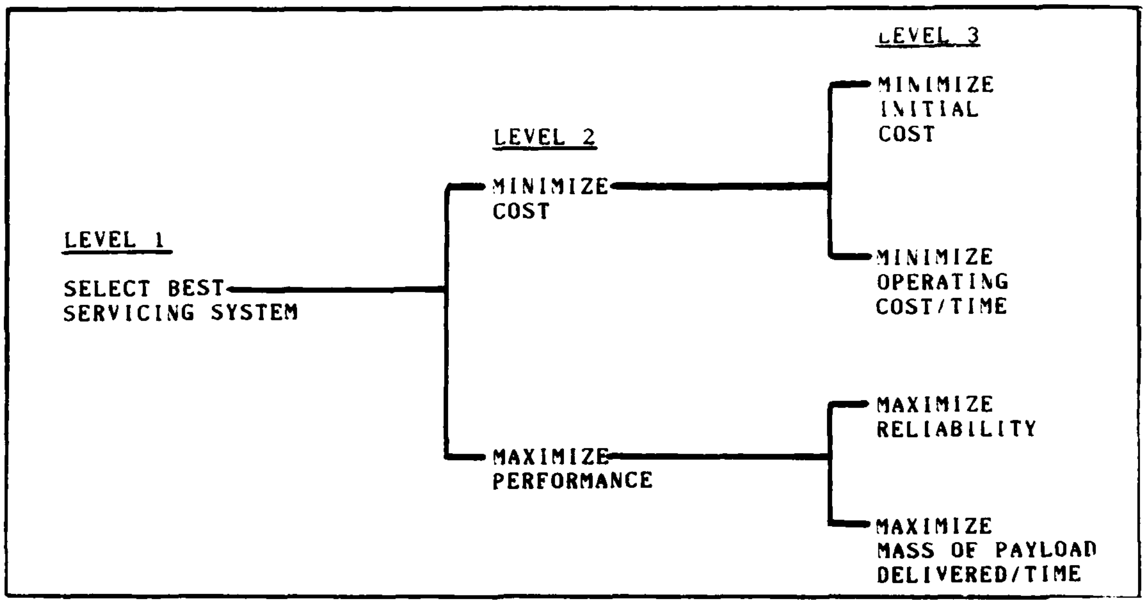

Figure 3.7 Simplified Hierarchy of Objectives

3.3 Capturing a Decision Maker's Weightings of Objectives (Crawford and Williams, 1985)

Once a hierarchy of objectives has been established, it is required to determine the preference or weighting that a decision maker credits to each objective. This is necessary to apply the hierarchy structure as described in section 3.1 to get an overall figure of merit for each system, and finally a ranking of systems. One method for soliciting these preferences is detailed in this section.

As described earlier, an objective hierarchy is a collection of objectives grouped according to levels (see Figure 3.1). Objectives at each specific level of the hierarchy depend upon the objectives at the lower levels. An objective at any level in the hierarchy may be ranked by a

ratio scale, relating its importance relative to a given objective at the level above it. It is then possible to construct a system of ratio scales which yields the relative importance (or weighting) of any objective at one level, to any other objective in a higher level.

Several ways exist to construct this system of ratio scales. Two methods commonly used are the geometric mean approach, and the Saaty eigenvalue/eigenvector approach. Due to the complexity in calculating the consistency ratio (to be explained later) for the geometric mean approach, the Saaty eigenvalue/eigenvector method will be used and explained for this study. The interested reader will find an excellent discussion of the geometric mean approach in a report by the RAND Corporation, titled "The Analysis of Subjective Judgement Matrices" (Crawford and Williams, 1985).

3.3.1 <u>Eigenvalue/Eigenvector Approach</u>. Thomas Saaty of the University of Pennsylvania developed a method for estimating subjective ratio scales using pairwise comparisons. In this method the analyst has the decision maker perform pairwise comparisons between the objectives. For each objective pair, the decision maker identifies not only which objectives are preferred, but also to what degree that objective is preferred over the other. A preference ratio scale is then determined for the objectives based upon eigenvector analysis of a matrix of pairwise comparisons.

In order to develop this matrix it is necessary to assign to each objective an estimate of utility. This is done in such a way that if U_i is the utility of the ith objective, then U_i/U_j is a measure of the utility of the ith objective to the jth objective. The vector $U_1, U_2, \ldots\ U_n$ will be called a ratio scale. A matrix can be constructed that is composed of the subjective estimates of all possible pairwise comparisons of the objectives. This yields the elements A_{ij} of the matrix in Figure 3.8.; each element A_{ij} represents the estimate U_i/U_j. Diagonal elements are all "1," since they represent the comparison of an objective to itself ($A_{ii}=U_i/U_i=1, i=1\ldots n$). The lower triangular elements represent the inverse comparison done on the upper triangular elements: $A_{ij}=1/A_{ji}$. Consequently, only half of the comparisons of objectives need be solicited for filling the matrix. The other half of the matrix is filled with the reciprocal from the judgements already made.

$$
\begin{array}{cc}
 & \begin{array}{cccc} \text{Obj } 1 & \text{Obj } 2 & \cdots & \text{Obj } n \end{array} \\
\begin{array}{c} \text{Obj } 1 \\ \text{Obj } 2 \\ \vdots \\ \text{Obj } n \end{array} & \left[\begin{array}{cccc} 1 & A_{12} & \cdots & A_{1n} \\ 1/A_{12} & 1 & \cdots & A_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ 1/A_{1n} & 1/A_{2n} & \cdots & 1 \end{array}\right]
\end{array}
$$

where:
$A_{12}=U_1/U_2$
or in general,
$A_{ij}=U_i/U_j$
(for $i,j=1,2,\ldots n$)

Figure 3.8 Pairwise Comparison Judgement Matrix

The choice of a scale to be used for making the comparisons between objectives is largely arbitrary. It has been shown that people generally find it difficult to rank more than about seven objects at a time (Saaty, 1980:p55). Saaty therefore recommends a subjective pairwise comparison scale consisting of the range of integers from one to nine including their reciprocals. This scale results in a value of "1" being assigned to pairs of objects of equal importance. The integers "3", "5", "7", and "9" correspond to descriptive words (9 stands for "absolute importance", 5 stands for "essential or strong importance", and so forth), and the integers "2", "4", "6", and "8" represent the intermediate values. Reciprocals of the integers are necessary for the judgements on half of the scale to ensure a recipro-

cal symmetric matrix. See Figure 3.9 for an example of a comparison between two objectives using Saaty's comparison scale.

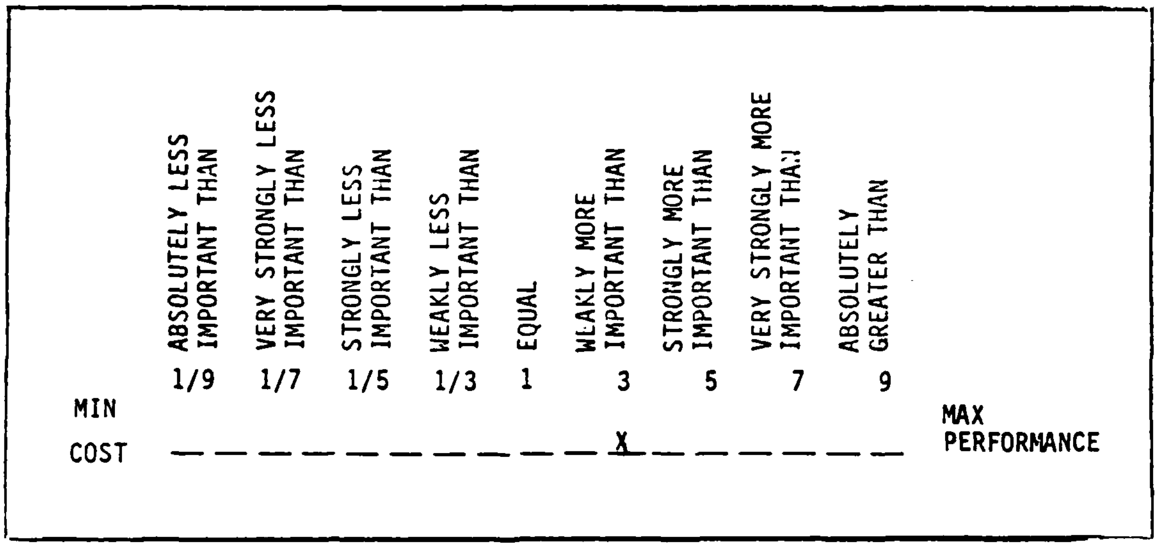

Figure 3.9 Example Using Saaty's Comparison Scale

If minimizing cost is weakly more important than maximizing performance, then the number "3" would be placed in the a_{12} position of the comparison matrix. The reciprocal "1/3" could immediately be placed in the A_{21} position.

Since A_{ij} estimates U_i/U_j, it follows immediately that

$$(A_{ij} \times A_{jk}) \approx A_{ik} \tag{3.7}$$

A matrix with positive entries that exactly satisfies (3.7) is called a consistent matrix. The ideal pairwise

comparison matrix demonstrates this property of consistency. As an example, if A is three times more important than B, and B is four times more important than C, it would be expected that A would be twelve times more important than C. Because human judgements are often inconsistent, a judge making pairwise comparisons would probably construct an inconsistent judgement matrix, unless the dimension was small. Recognizing this, it is necessary to find a way to construct a ratio scale which best reflects the information in the matrix.

As defined earlier, $A_{ij} = U_i/U_j$. For the consistent case let $A_{ij} = W_i/W_j$, where the comparisons are based upon exact measurements, that is, $W_1,\ldots,W_n$ are already known. Let matrix A have the components of A_{ij}, and matrix $\mathbf{W}$ have the components W_i. Then for the consistent case:

$$A = \begin{bmatrix} W_1/W_1 & W_1/W_2 & \cdots & W_1/W_n \\ W_2/W_1 & W_2/W_2 & \cdots & W_2/W_n \\ \vdots & \vdots & & \vdots \\ W_n/W_1 & W_n/W_2 & \cdots & W_n/W_n \end{bmatrix} \quad \text{and} \quad \mathbf{W} = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix}$$

An important result of this is that: $\mathbf{AW} = n\,\mathbf{W}$, where n is the dimension of matrix A. In the practical case, A_{ij} deviates from W_i/W_j, but for the consistent case (the eigenvalues) are numbers that satisfy $AX = \lambda_{max} X$. For the consistent case all eigenvalues are zero except

for one, which is n. For the inconsistent case, small changes in the entries of A_{ij}, of the positive reciprocal matrix **A**, induce small changes in the eigenvalues. These small variations in A_{ij} from consistency keep the largest eigenvalue, λmax, close to n, and the remaining eigenvalues close to zero. Therefore, for the inconsistent case, **U**, which satifies:

$$\mathbf{A}\,\mathbf{U} = \lambda max\,\mathbf{U} \tag{3.8}$$

is the eigenvector associated with λmax. This **U** closely approximates the weights of the consistent case. For further computations, **U** is normalized because the weights for the objectives being compared must sum to one. In summary, Saaty proposes that the normalized eigenvector corresponding to the maximal eigenvalue of the judgement matrix best estimates the ratio scale for inconsistent matrices (Saaty, 1980:p49).

Frobenius gives a theorem for matrices with positive entries (Franklin, 1968) which guarantees that any judgement matrix has a positive eigenvalue which is greater than all other eigenvalues in absolute value. This maximal eigenvalue has a corresponding eigenvector which is positive in all of its components; it is called the dominant eigenvector. The dominant eigenvector is a continuous function of the elements within the judgement matrix, and if the matrix is consistent, the eigenvector gives the unique scale (to within scalar multiplication). If the elements have small

perturbations due to the human judgement process, the dominant eigenvector will yield a scale only slightly different from the scale of an underlying consistent judgement matrix.

Saaty developed an index of consistency for this judgement matrix. He demonstrated that an nxn judgement matrix whose only non-zero eigenvalue is n must be consistent. The maximal eigenvalue M for an inconsistent judgement matrix is strictly greater than n. Using the normalized difference: $u = (M-n)/(n-1)$ results in the index of consistency u, of an nxn judgement matrix with maximal eigenvalue M. It can be seen that this index of consistency increases as perturbations from the consistent values of the matrix components increase.

The mechanism by which small perturbations of matrix components give rise to a given deviation in the maximal eigenvalue is complicated. Saaty describes an empirical investigation of this in which he determines the consistency indices corresponding to randomly generated judgement matrices of different dimensions. Because the eigenvector does not fit into any standard statistical framework, there is not a readily available technique against which deviations from consistency can be measured.

Consider an example that uses the hierarchy shown in figure 3.5. To determine the "strengths" or weightings between elements within the hierarchy, it is necessary to do

a pairwise comparison at each subgroup within each level. Each element within the subgroup is compared to every other element within the subgroup. This determines the importance that element has with respect to every other element on its level. Figure 3.10 demonstrates how the decision maker's comparisons were recorded by the analyst for each of the elements within the hierarchy. Once the comparisons have been made, the results are placed in matrix notation as shown in figure 3.11. The eigenvalues are then found. The dominant eigenvector (eigenvector associated with the maximal eigenvalue) when normalized, directly gives a vector representing the respective objective weightings. These resultant weightings are shown in Figure 3.12.

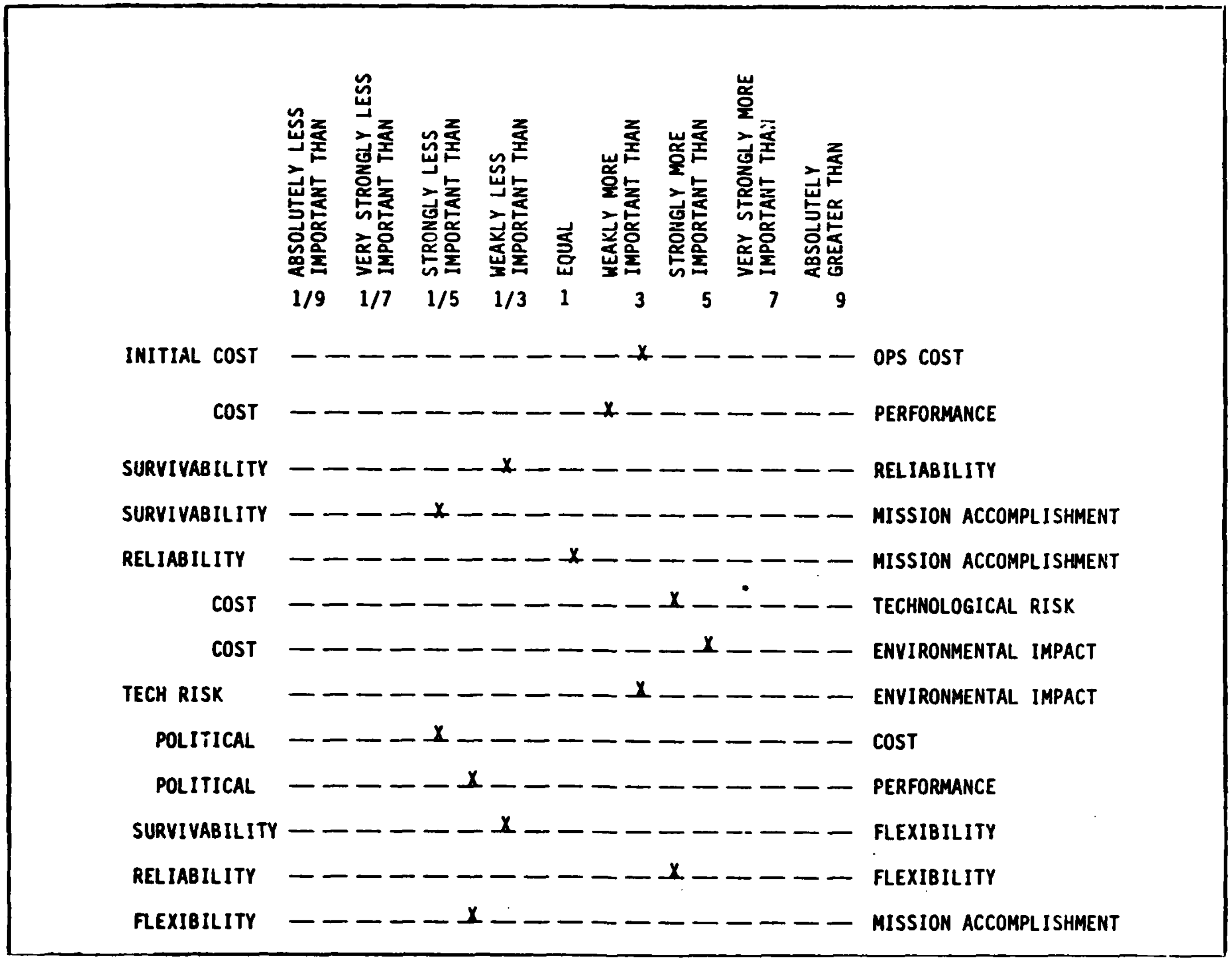

Figure 3.10 Recording Decision Maker's Comparisons

$$
\begin{array}{l} \\ \text{COST} \\ \text{TECH RISK} \\ \text{ENVIRONMENT IMPACT} \end{array}
\begin{array}{c}
\begin{array}{ccc} \text{COST} & \text{TECH RISK} & \text{ENVIR IMPACT} \end{array} \\
\begin{bmatrix} 1 & 4 & 5 \\ 1/4 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix}
\end{array}
$$

Max Eigenvalue 3.086
Normalized Eigenvector 0.6738, 0.2255, 0.1007

$$
\begin{array}{l} \\ \text{INITIAL COST} \\ \text{OPS COST} \end{array}
\begin{array}{c}
\begin{array}{cc} \text{INITIAL COST} & \text{OPS COST} \end{array} \\
\begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix}
\end{array}
$$

Max Eigenvalue 2.000
Normalized Eigenvector 0.75, 0.25

$$
\begin{array}{l} \\ \text{SURVIVE} \\ \text{RELIAB} \\ \text{FLEX} \\ \text{MASS P/L DELIVER} \end{array}
\begin{array}{c}
\begin{array}{cccc} \text{SURVIVE} & \text{RELIAB} & \text{FLEX} & \text{MASS P/L DELIVER} \end{array} \\
\begin{bmatrix} 1 & 1/3 & 1/3 & 1/5 \\ 3 & 1 & 4 & 1 \\ 3 & 1/4 & 1 & 1/4 \\ 5 & 1 & 4 & 1 \end{bmatrix}
\end{array}
$$

Max Eigenvalue 4.190
Normalized Eigenvector 0.079, 0.3737, 0.1359, 0.4114

$$
\begin{array}{l} \\ \text{POLITICAL} \\ \text{COST} \\ \text{PERFOR} \end{array}
\begin{array}{c}
\begin{array}{ccc} \text{POL} & \text{COST} & \text{PERFOR} \end{array} \\
\begin{bmatrix} 1 & 1/5 & 1/4 \\ 5 & 1 & 2 \\ 4 & 1/2 & 1 \end{bmatrix}
\end{array}
$$

Max Eigenvalue 3.025
Normalized Eigenvector 0.09739
0.5695
0.3331

Figure 3.11 Decision Maker's Comparisons in Matrix Notation

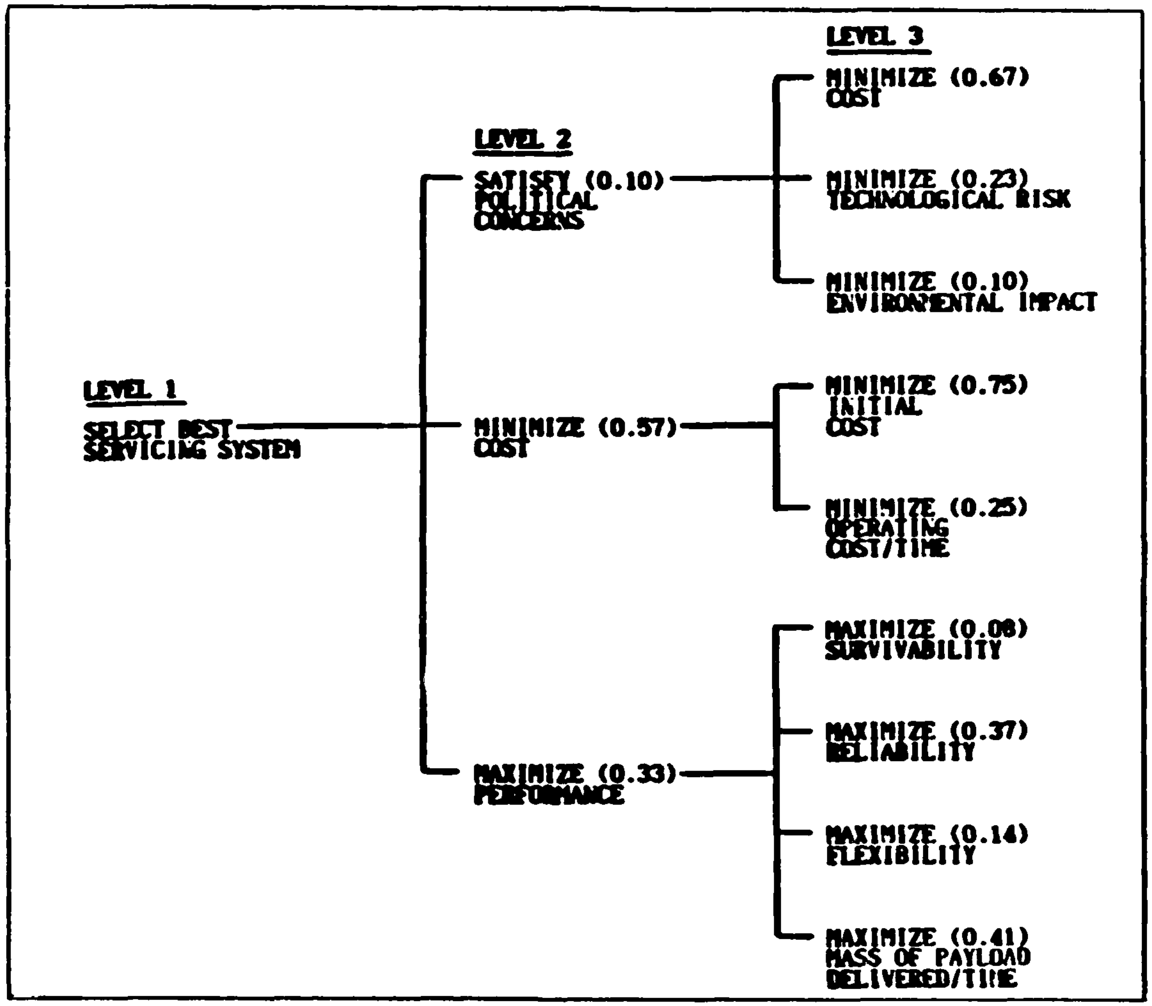

Figure 3.12 Hierarchy of Objectives with Resulting Weights

3.4 Calculation of the Value Functions

3.4.1 Introduction. The procedures described in the previous sections enable the analyst to develop a weighted hierarchy of objectives based on the decision maker's preferences. The analyst must now work with the decision maker to construct a value function for each performance index in the hierarchy tree. As a reminder, the performance indices are attributes that measure the degree to which the lowest level objectives are attained. Using the weighted hierarchy tree and the individual value functions, a scalar figure of merit can be determined for each candidate solution in the non-dominated solution set. The figure of merit has the advantage of being a single index that represents the relative preference the decision maker has for a particular solution. The NDSS may then be rank-ordered using these figures of merit, to provide the DM with a ranked listing of optimal solutions based on his own preferences. This section describes how value functions are solicited from the decision maker.

A value function is a mapping of the measurement of a performance index to the utility or "value" that the decision maker associates with it. This function is easily graphed, with the range of measures of the performance index on the abscissa, and the associated values for each measure, $V_i(X_i)$, on the ordinate. The endpoints for the range of measures on the abscissa may be selected in several ways.

One method is to set the lower bound at the least acceptable measure and the upper bound at the most acceptable measure. The analyst then solicits the decision maker for his "values" at three points between these endpoints. This information allows the analyst to fit a curve through those points. The resultant curve represents the decision maker's value function for that performance index. The following example demonstrates these procedures.

3.4.2 Value Function Curve Shape. Figure 3.7 represents a simple hierarchy of objectives for selecting a satellite servicing system. It has four performance indices -- initial cost, (operating cost)/time, reliability, and (mass of payload delivered to orbit)/time. This example demonstrates construction of a value function for initial cost.

It is assumed that the least acceptable initial system cost is $100 billion and the most acceptable initial cost is $10 billion. If the value "0" is assigned to $100 billion and the value "1" is assigned to $10 billion, the value function curve is described by the set of points that lies between the two endpoints. There are different techniques that may be used for determining the shape of this curve. One of the methods described in section 3.1 is the midvalue splitting technique. This technique requires one to find the midpoint value between the upper and lower bounds. The analyst can determine this value during a session with the decision maker by asking him to answer the question in the

following scenario (Chankong and Haimes, 1983:188):

> The values of all performance indices (except initial cost) are fixed at their lowest levels. Suppose you are given two situations:
>
> 1) The initial cost of a satellite servicing system is first estimated to be $55 billion. Later you are told that a mistake was made - the initial cost should be $10 billion.
>
> b) The initial cost is estimated to be $100 billion. Later you discover it should be $55 billion.
>
> Would you be more delighted in your discovery in the first situation or the second, or would you feel equally delighted in both cases?

If the decision maker shows greater preference for the first situation, a point should be picked between $10 billion and $55 billion, say $45 billion, and the question repeated with $45 billion replacing $55 billion. If the decision maker is less delighted to go from $45 billion to $10 billion than to go from $100 billion to $45 billion, yet another point in the preferred range should be picked, say $50 billion, and the process repeated. If the decision maker is exactly as delighted to go from $100 billion to $50 billion as from $50 billion to $10 billion, the midpoint

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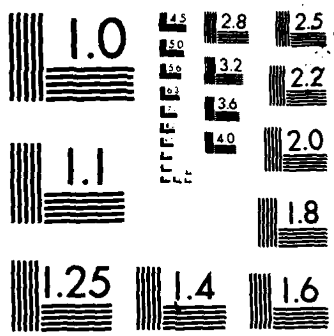

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between \$10 billion and \$100 billion is X(0.5) = \$50 billion. Using the same process the midpoints for X(0.25) and X(0.75) may be found. Suppose that X(0.25) = \$75 billion and X(0.75) = \$30 billion. To check for consistency, the decision maker should verify that he would be equally delighted to go from \$50 billion to \$30 billion as to go from \$75 billion to \$50 billion. If not, X(0.5) should be adjusted accordingly, and X(0.25)and X(0.75) should be checked again. Suppose the values X(0.25) = \$77.5 billion, X(0.5) = \$55 billion, and X(0.75) = \$32.5 billion are found to be consistent. Then a plot of these points can be made and an appropriate curve can be fitted through these points as shown in Figure 3.13. The shape of this curve should be examined by the decision maker to confirm its validity for his preferences.

Computer programs are available that will aid in finding the shape of each value function. MADAM (Stimpson,1983) is one such package that uses the midvalue splitting technique and curve-fits the points to one of five

curves (see figure 3.14):

$$v = b_0 + b_1 x \tag{3.7}$$

$$v = b_0 + b_1 x^2 \tag{3.8}$$

$$v = b_0 + b_1 e^x \tag{3.9}$$

$$v = b_0 + b_1 (x)^{1/2} \tag{3.10}$$

$$v = b_0 + b_1 (\ln x) \tag{3.11}$$

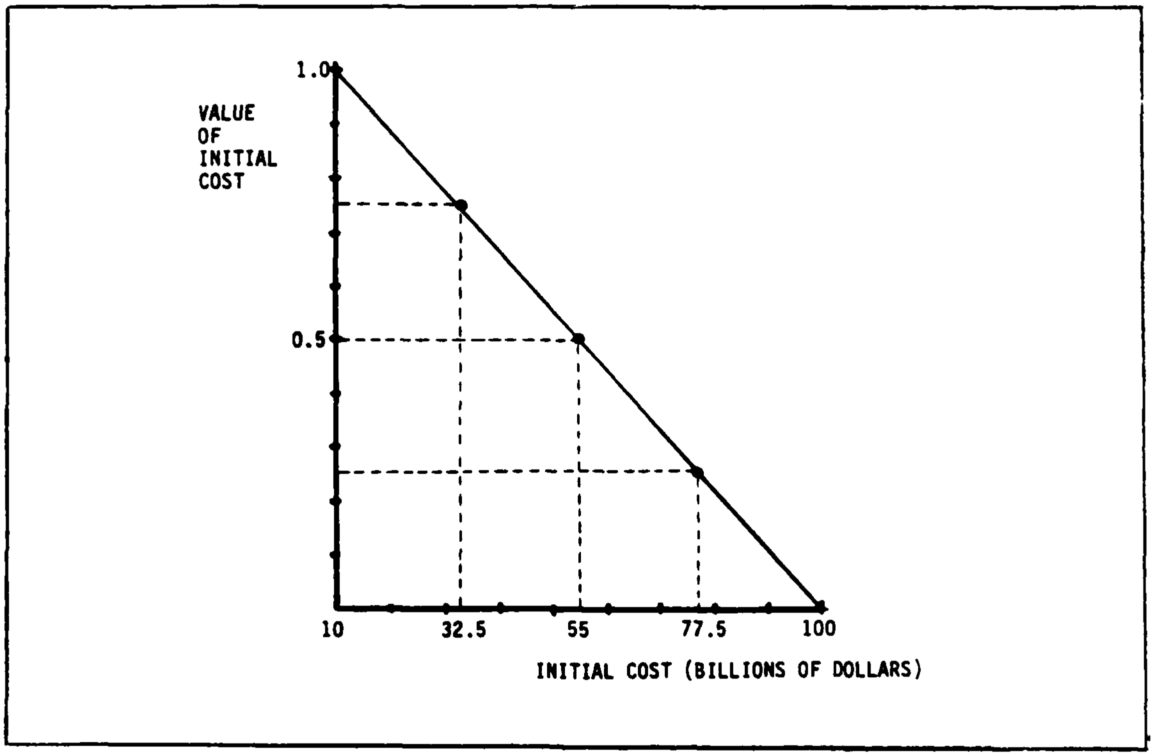


Figure 3.13 Value Function Curve for Initial Cost

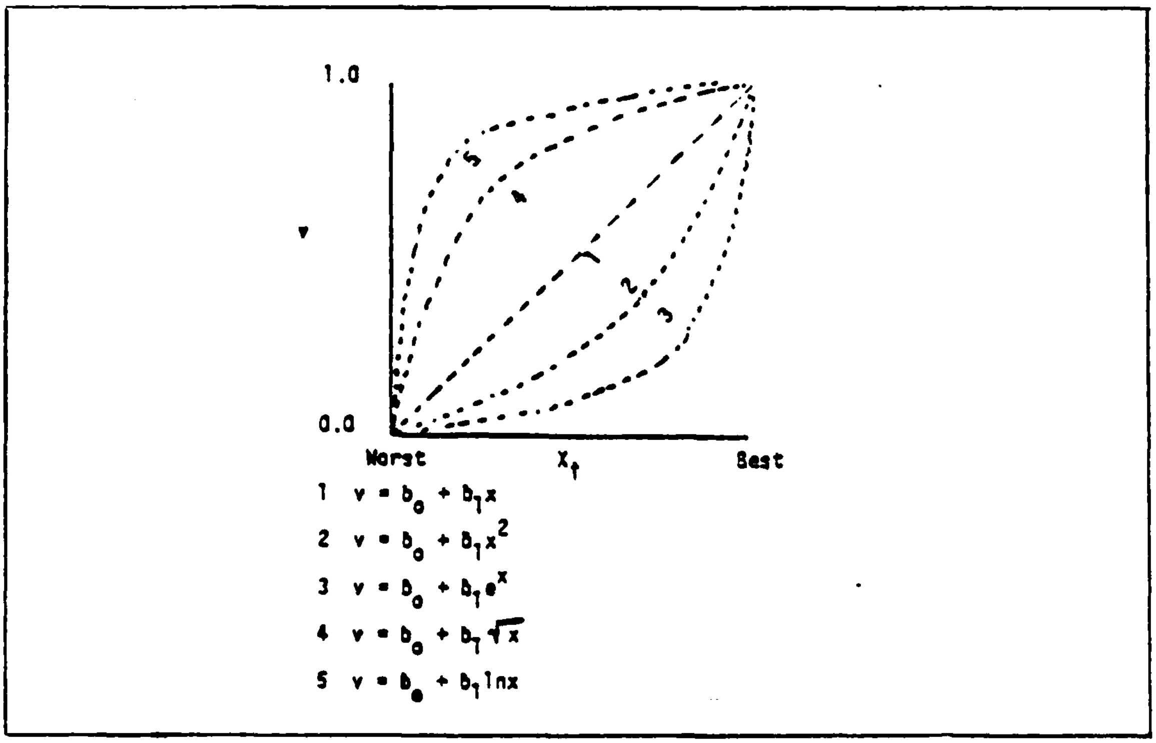


Figure 3.14 Curve-Fits for Value Functions in MADAM
(DeWispelare and Stimpson,1983:16)

A value function must be determined for each performance index; it relates the measure of that PI to the utility that measure has in the mind of the decision maker. Thus for the simple hierarchy tree of Figure 3.7, a value function would be determined for initial cost, operating cost/time, reliability, and mass of payload delivered/time.

Since every individual has unique preferences, it is unlikely that two decision makers will have the same exact value function for any particular performance index. For the performance indices being used in this study, "more" is "better" in general, so linear value functions would not be unexpected. Consequently, linear value functions have been used for all decision makers in this study to emphasize differences among decision makers based on preferences alone.

As seen from the example above, to find the value function curve shape, the range of the performance index must be specified. One method for specifying the range is to find the highest and lowest measures of the PI from the NDSS. The appropriate value, zero or one, is assigned to those measures accordingly, and one of the several techniques is then used to determine the points in-between.

It is important that an identical approach be used for assigning values for each PI. In the above example, the objective was to minimize initial cost. Consequently, the

value "0" was assigned to the least acceptable cost, and the value "1" was assigned to the most acceptable cost. Likewise, if the objective is to maximize reliability, the value "0" should be assigned to the least acceptable reliability, and the value "1" to the most acceptable reliability. This will keep the comparisons in the correct order, even though the numerical measures of the PI may be inverse relationships. In other words, the smallest initial cost is best, while the largest reliability measure is best.

Caution must also be exercised when setting up the range on the value function for each PI. The decision maker must compare the ranges for each performance index and ensure that the values are comparable. For example, suppose the initial cost of a system amortized for the year, ranged in the NDSS between $10 billion and $100 billion, and the operating cost per year ranged between $500,000 and $2 million. Using these measures to specify the range for determing the value function is equivalent to saying that $10 billion of initial cost has the same value to the decision maker as $500,000 of operating cost. If the decision maker involved feels that this is not a valid comparison, he has one of two choices. One solution is to create a pseudo-range; that is, adjust the endpoints of the range until the comparisons are valid. If, however, the decision maker feels that one dollar should have the same "value" all the time, regardless of what it is measuring, he should use

identical ranges for all performance indices using dollars as the measure. This, in some instances, will compress the performance index "values" towards one end of the scale. However, there is nothing inherently wrong with that if it accurately represents the decision maker's values. This same procedure applies to comparisons for all performance index measures, be they dollars versus dollars, or reliability versus pounds of mass delivered to orbit. This consistency in scaling the value functions for each performance index is also necessary to allow sensitivity analyses for the decision maker's values. Sensitivity analysis of the value system is examined in Chapter VI.

3.5 Calculation of the Figure of Merit

Once the value functions are defined, each performance index in the NDSS will have a distinct "value" associated with it. This section demonstrates how a value function is used with the weighted hierarchy tree to obtain a figure of merit for each solution in the NDSS.

Consider the weighted hierarchy tree in Figure 3.15, with performance indices Z_1 (initial cost), Z_2 (operating cost/time), Z_3 (reliability), and Z_4 (mass of payload delivered/time).

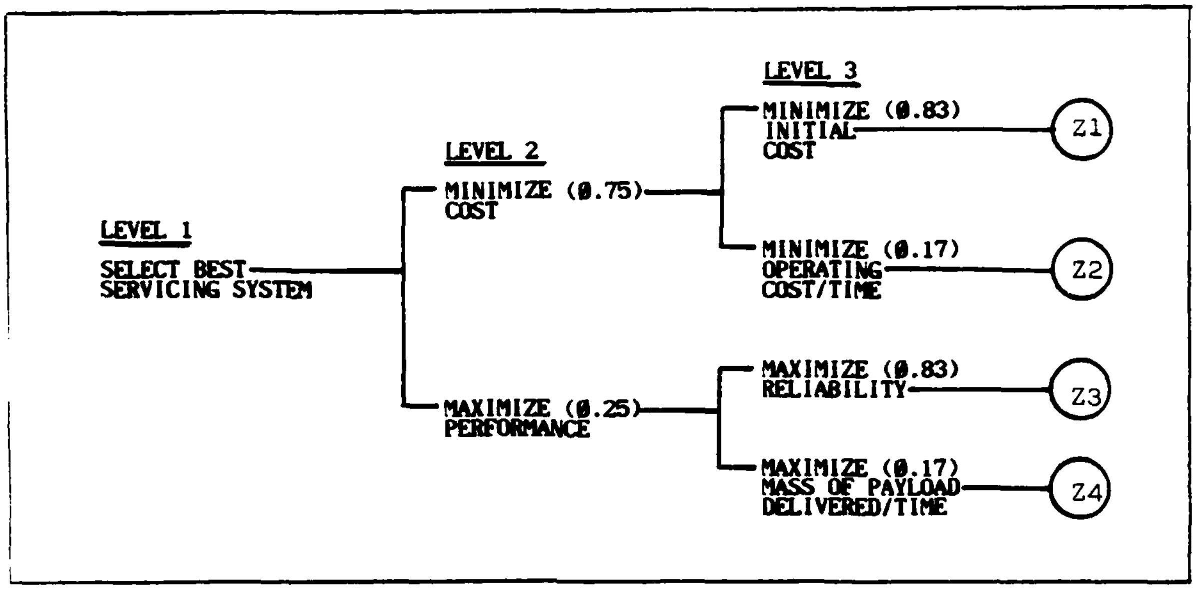


Figure 3.15 Weighted Hierarchy Tree for Value System

Assume one of the solutions in the NDSS is the following:

Z_1 = \$77.5 million

Z_2 = \$32.5 million/year

Z_3 = .90

Z_4 = 43800 kg/year

If the ranges of the performance indices and the shapes of the value functions are known, a value for the level of each PI can be found. The following values were derived from the appropriate value function curves (Figures 3.16 to 3.19):

$V(Z_1) = V(77.5\ M) = .25$

$V(Z_2) = V(32.5\ M) = .75$

$V(Z_3) = V(.90) = .80$

$V(Z_4) = V(43800) = .60$

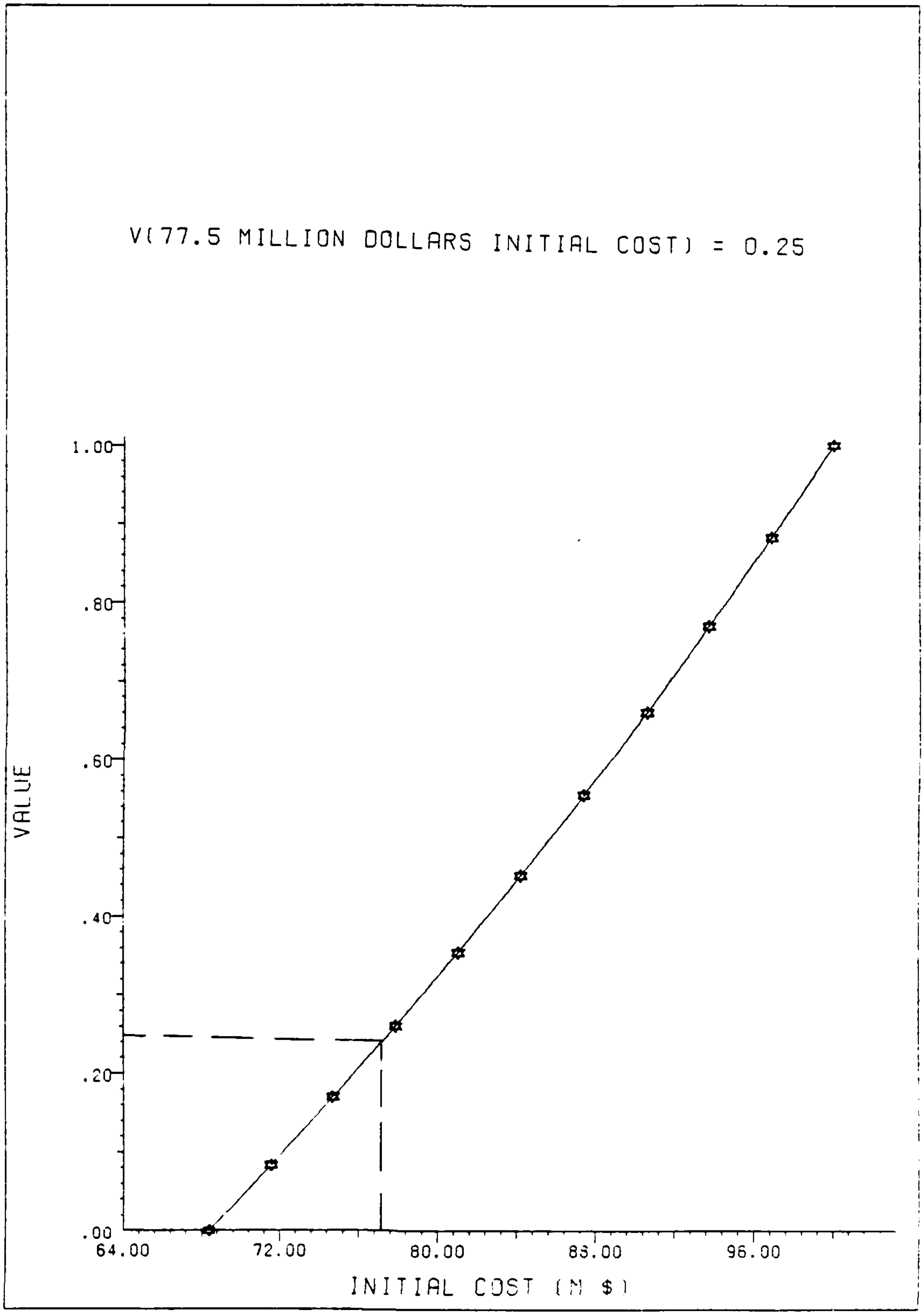


Figure 3.16 Sample Value Function Curve for Initial Cost

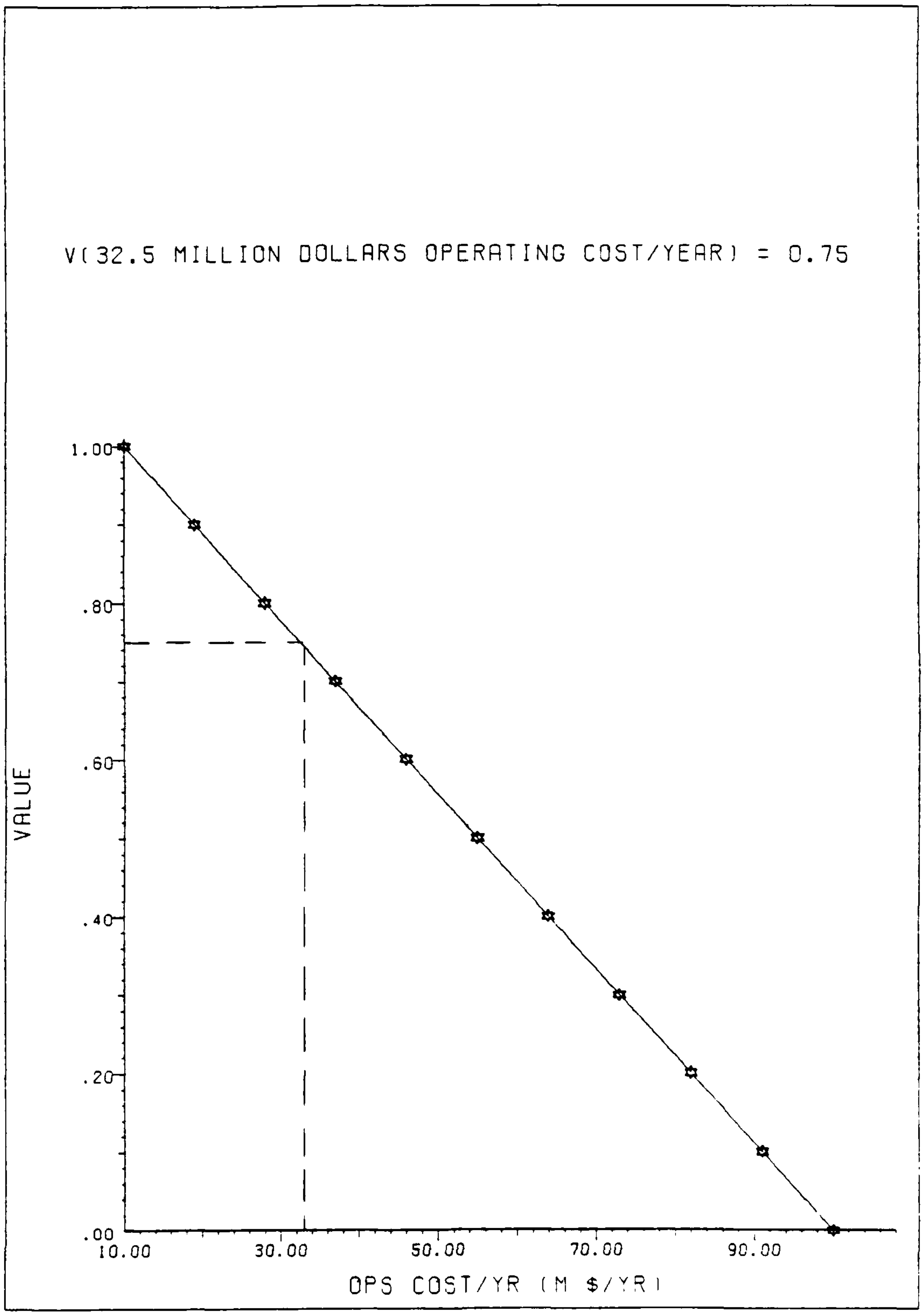


Figure 3.17 Sample Value Function Curve for (Operating Cost)/Time

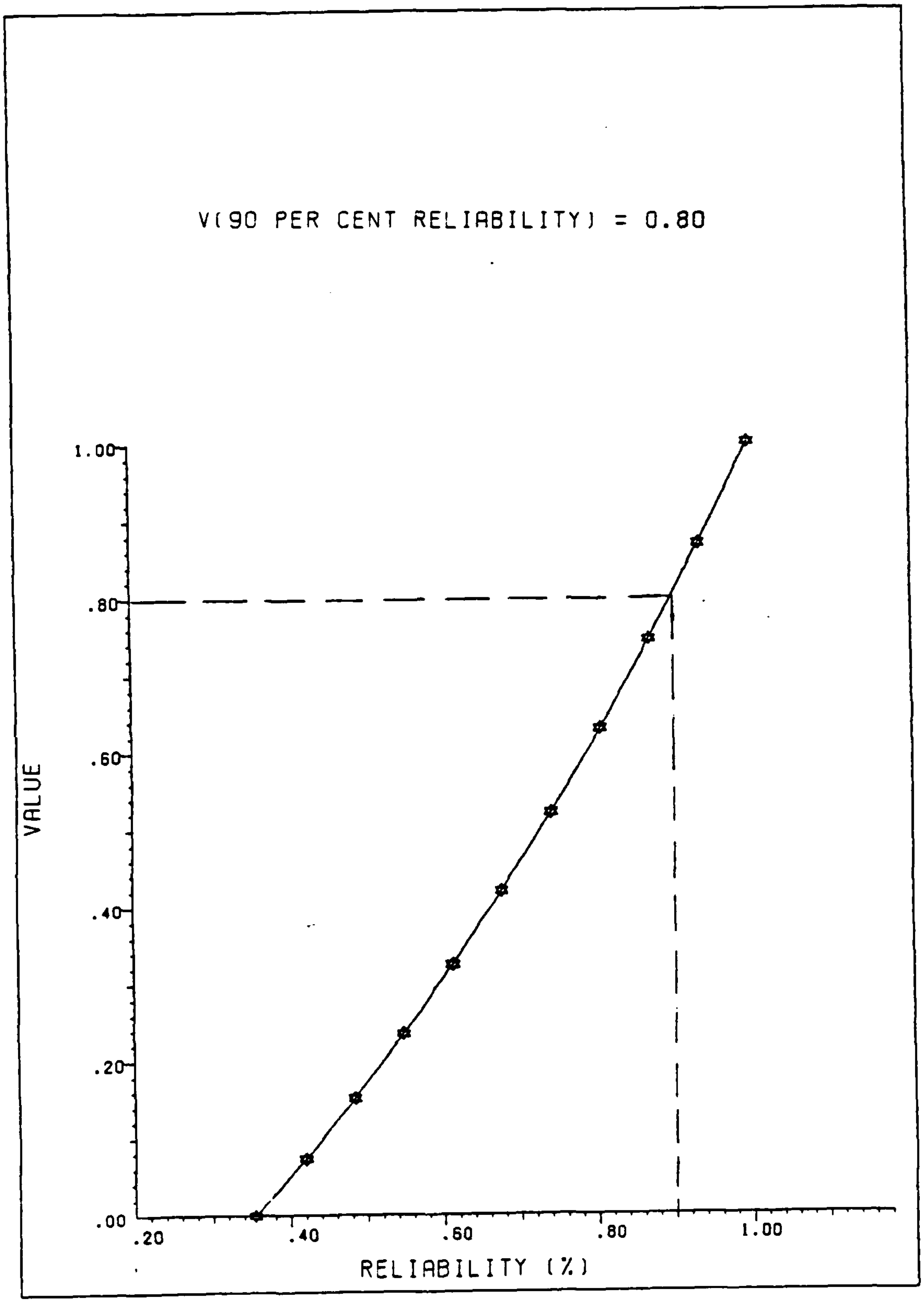


Figure 3.18 Sample Value Function Curve for Reliability

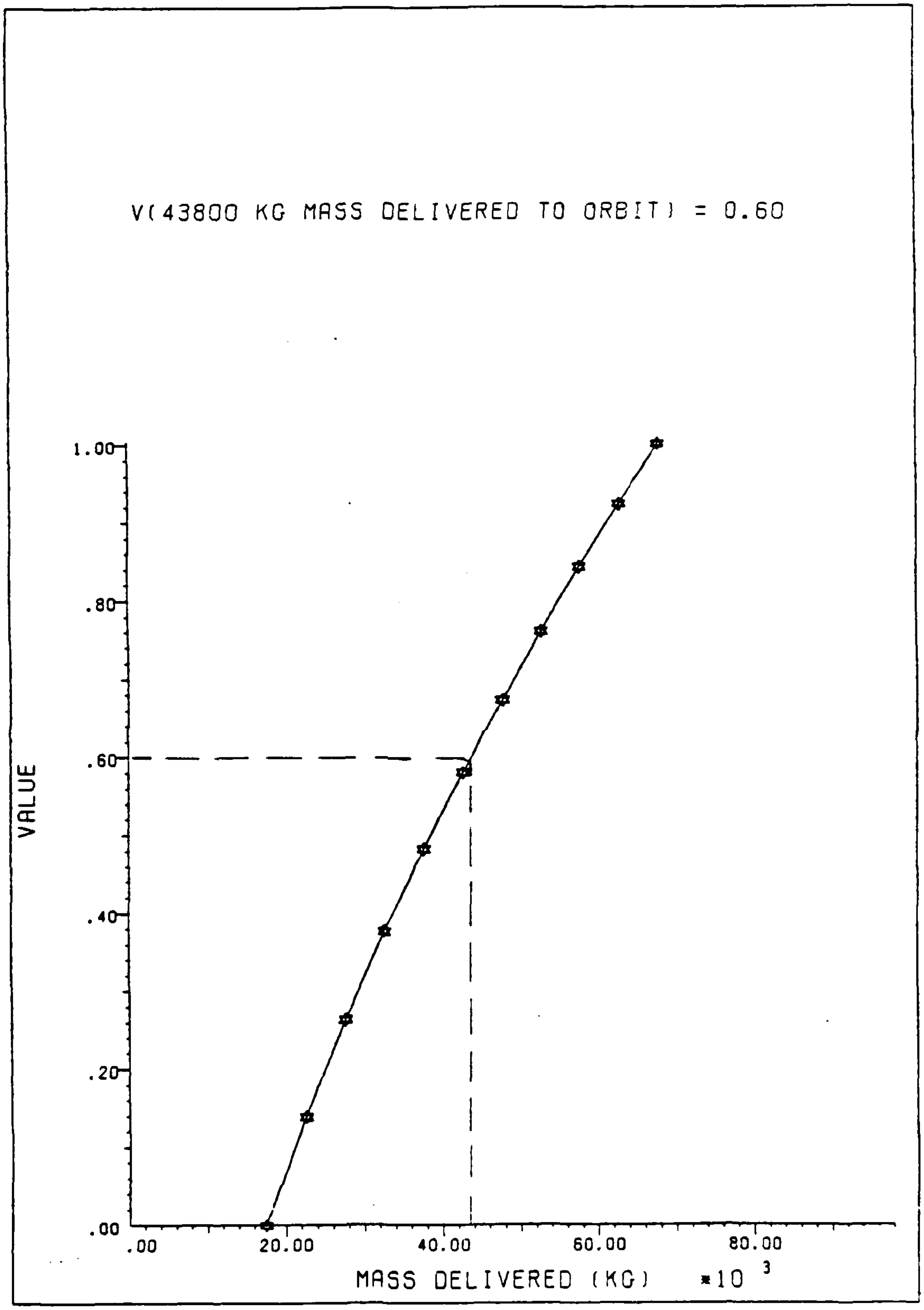


Figure 3.19 Sample Value Function Curve for Mass of Payload Deliver

Note that the value functions range between zero and one. Because of this and because each candidate solution in the NDSS uses the same single-attribute value function for each individual PI, the "values" from the functions can be applied directly to the weighted hierarchy tree. Since an additive value function is being used, the figure of merit is calculated by multiplying the PI "value" by the tree level weight, and summing at each level of the tree. The value at each level (except the bottom level) is simply the summation of the (weight x value) calculations of the level just below it.

From Figure 3.15, where

TC is Total Cost

PERF is Performance

IC is Initial Cost

OC is Operating Cost

REL is Reliability, and

MPD is Mass of Payload Delivered

Wt is hierarchy weighting, and Val is value of PI from value function

$$\begin{aligned}
\text{Figure of Merit} &= (\text{Wt of TC}) * (\text{Val of TC}) \\
&\quad + (\text{Wt of PERF}) * (\text{Val of PERF}) \\
&= (\text{Wt of TC}) * [(\text{Wt of IC}) * (\text{Val of IC}) \\
&\qquad\qquad + (\text{Wt of OC}) * (\text{Val of OC})] \\
&\quad + (\text{Wt of PERF}) * [(\text{Wt of REL}) * (\text{Val of REL}) \\
&\qquad\qquad + (\text{Wt of MPD}) * (\text{Val of MPD})] \\
&= (0.75) * [(.83)(.25) + (.17)(.75)] \\
&\quad + (0.25) * [(.83)(.80) + (.17)(.60)] \\
&= 0.44275
\end{aligned}$$

When these calculations are repeated using the appropriate "values" for each solution in the NDSS, a scalar figure of merit is derived for each solution. The NDSS solutions may then be rank-ordered using the figure of merit as the measure of desirability for each system solution. Now the analyst can present to the decision maker a list of optimal solutions that have already been ranked by the DM's own preferences. Chapter VI demonstrates ranking of the solutions in an NDSS.

For a large NDSS it may be desirable to automate these calculations using a computer. One such computer program was developed for the simple hierarchy of Figure 3.15, and may be found in Appendix C.

3.6 Value System Summary

Every decision maker has a unique value system, which is simply a formal mathematical representation of his preferences. If certain axioms are met, a mapping of those preferences to a value scale can be accomplished. This mapping is referred to as a utility function for mappings involving "uncertain alternatives." For functions with "certain alternatives," it is called a value function. The two most common functional forms of these functions are the additive and the multiplicative forms. The appropriate form is identified by satisfying certain necessary and sufficient conditions of independence among the objectives in the problem.

A common structural formulation for the objectives in a multiple-objective problem is in the form of a hierarchy tree. By accomplishing pairwise comparisons between objectives at each level of the tree, a weighting for the preference of each objective may be determined.

At the lowest level of the tree are the objectives to which measurable descriptors can be applied. Each one of the descriptors, or attributes (performance indicies), has an associated value function (or utility function). This function, which has values between zero and one, describes the utility that the decision maker places on the range of the measure of that attribute.

Each solution out of the nondominated solution set (each representing a different candidate system configuration) will have an associated value for each performance index measure. These values can be directly applied to the weightings in the hierarchy tree. For an additive value function, the objective weighting is multiplied by the performance index "value", and summed at each tree level to determine the value for the objective in the level above it. This is continued until a scalar figure of merit is derived at the top of the tree. In this way, each candidate system configuration from the nondominated solution set can be given a single "measure of desirability" or "figure of merit." These figures of merit may then be rank ordered to provide the decision maker with a ranked listing of solutions based on his own preferences.

Chapter VI demonstrates the calculation of a figure of merit for each candidate solution in a nondominated solution set, using the preferences of different decision makers. The solutions are then ranked using the figures of merit to give the "best solution" for each decision maker.

IV. Alternatives Generation (System Synthesis and Modeling)

4.1 Introduction.

The purpose of modeling is to describe in some fashion the system under study in such a way as to be useful in analyzing the performance of that system. The type of model used in this effort is an analytical model (set of equations) cast into a statespace form. The purpose of this chapter is to present in a clear and logical fashion what these equations represent. However, the number of equations is quite large (over 27) and many of them are non-linear. Rather than list and describe each equation separately, the equation development process is presented. In this way the *definitions*, *assumptions*, *and limitations* of the model equations should become clear.

Typically, equations to represent a complex system such as a Satellite Servicing System (SSS) cannot be developed in one step. When an analyst first starts to build such a model he may only have a partial idea of the important factors in the problem and the simplifications that can be made. Therefore, it is often advantageous to model the inter-relationships of the complex system iteratively, starting from the most basic conceptual models and evolving through stages to its final form. Ultimately only those factors relevant to the problem should be included in the model. However, for many complex systems the concept of the

problem and its scope are not readily apparent. Often, it is only through repeated iterations of forming, implementing, and analyzing models of increasing detail that an analyst can get a good feel for the problem, its scope, and the important factors to describe the system in light of the problem definition. For clarity, the results of this iteration process (as used in this study) are presented in two sections.

The first section (conceptualization) deals with the evolution of the basic conceptual models just prior to equation development. These "picture" models are first formed through model synthesis. During this process, important design objectives for a military SSS are identified and candidate subsystems are defined to perform the system functions of delivering mass from earth to orbit and delivering mass from orbit to the satellites. Combining these subsystems in every way possible generates forty-five candidate SSS architectures. These architectures are analyzed on a qualitative level for realizability. Based on defined assumptions, twelve SSS architectures are identified as "feasible." These feasible systems are then qualitatively compared to each other in terms of how well they achieve the performance objectives. The result is a set of four candidate SSS architectures identified for further detailed modeling in the form of equation development.

The second section (analytical models) describes the quantitative models developed for the chosen architectures. The level of detail represented by the equations could not be used to differentiate between two of the systems; therefore, one equation set models two systems. A total of three analytical statespace models is presented. First, the form and terms of a statespace model are defined, followed by a qualitative discussion of the three model equation sets. A complete listing of the three sets of analytical equations is in Appendix D.

The application of multiple objective optimization theory (MOOT) techniques to one set of these equations, and the analysis of the subsequent results, is presented in Chapter V. One purpose of analysis is to determine the impact of modeled states on the overall performance of the system. If changing a state, such as time between launches of a launch vehicle, has little effect on the performance of all systems considered, then that state variable (or associated equations) can either be fixed at a constant or removed from the model. This demonstrates the importance of iteratively forming, implementing, and analyzing a model throughout its development. It should be noted that further refinement of the model equations is possible many times due to the results of analysis techniques such as those in chapter V.

4.2 Model Conceptualization

4.2.1 System Synthesis. Before developing model equations to describe candidate systems, the concept of the system must be formed. This synthesis process is concerned with answering several questions: What are the objectives of the system with respect to the problem statement? What are the alternative approaches for attaining each objective? How is each approach described? How does one measure attainment of each alternative approach? (Sage, 1977:73)

The model will be used to measure the performance of the candidate SSS it is designed to represent. As is the case with many problems, there are multiple objectives (many conflicting) to which a military SSS can be designed. During the initial synthesis the following seven objectives were thought to be important from a military viewpoint: low operating costs, low initial costs, high mass delivered to satellites, high survivability, high flexibility, high reliability, and improved satellite performance.

Since the SSS under study is assumed to be purchased and operated by the Department of Defense (DoD), initial and operating costs will be important to a DoD level decision maker. Initial cost is a key factor to get funding approval and support, while operating cost is important for DoD budgetary planning.

How well a SSS accomplishes its mission is important to describe to the funding authority what he is getting for his money. This objective should be a measure of how well the system does the task it was designed to accomplish. If for example, an automobile was the system of interest this would be analogous to asking how fast it will go, how many people it can carry, or how comfortable the ride is for the people. In the SSS system one measure of mission accomplishment is how much mass (satellite expendables and parts) the SSS can deliver to the satellites over a period of time.

National Security Decision Directive 42 (NSDD-42) announced 4 July 1982 and the DoD Space Policy (Dept. AF ,1985:Ch 15) state that future space systems must be built with survivability, flexibility, and reliability in mind. One of the unique requirements for most military systems (as compared to non-military) is the requirement to operate in an adverse environment or in less than ideal conditions. Survivability is a measure of the system's ability to perform under these conditions. NSDD-42 states "The United States will pursue survivability and endurance of space systems .... to perform the mission" (Dept. AF ,1985:15-8). Survivability also includes a space system's ability to survive meteoroid collisions and the effects of space radiation (Dept. AF ,1985:1-10).

The flexibility of a SSS is a measure of the ability of a system to operate in unforseen or diverse situations. The

DoD Space Policy (Dept. AF ,1985:15-10) requires "the availability of an adequate launch capability to provide flexible and responsive access to space to meet national security requirements." Although this requirement specifies launch systems, it seems logical to assume this policy of flexibility would extend to all space systems. In this study the flexibility objective is intended to be a measure of the SSS ability to perform a wide variety of potential tasks. In the case of an SSS, flexibility may be the deciding factor between selecting a manned or robotic system.

Current and future space systems are extremely expensive; therefore, their accuracy, efficiency, and dependability is of paramount importance. The Space Handbook (Dept. AF ,1985:10-1) states:

> "The advent of missiles and space systems has outmoded the 'fly and fix' philosophy. Good systems must operate when fired ... To accomplish this end both manufacturers and operators of space systems must pay more to attention than ever before to the reliability of the system as a whole ... Reliability is a term meaning the probability that equipment will perform a required function under specified conditions, without failure, for a specified period of time".

Another acceptable definition is the probability a system will be able to perform a specified function when required. In this study the reliability objective is intended to be a measure of the SSS ability to perform a specific mission.

Finally, how effectively a SSS improves the performance of satellites may be important to the decision maker

justifying the need for a SSS. The design, production, and deployment of a servicing system is of no value if the performance and availability of the serviced satellites are not improved.

In addition to establishing what the important objectives of the sytem are, the boundaries of that system must be identified. For without the concept of boundaries the system description (equations) could grow without end. In this study, the boundaries of a SSS are established by describing a SSS in terms of its two functional areas: (1) getting mass from Earth to orbit and (2) getting that mass from orbit to a satellite needing service.

Various subsystems are defined to accomplish these two functions as depicted in Figure 4.1. The objective of the study is to identify one or more configuration alternatives for the SSS, using combinations of the subsystems which accomplish the two mission functions. The following describe these subsystems in detail.

Mass from Earth to orbit (Launch systems)

Fixed High-G (FHG) launch system: A mass delivery system which launches from a fixed location. The acceleration of the vehicle is beyond human tolerance levels (about 5 g's) for an extended period of time and beyond sensitive electric equipment design loads. This is envisioned to be a swift and economical mass delivery system. A hydrogen blast tube (Eklund, 1984) could be such a system.

Mobile High-G (MHG) launch system: Similar to an FHG except the launch site is not geographically fixed. This subsystem adds a degree of survivability due to the mobile launch location.

Fixed Low-G (FLG) launch system: A mass delivery system which launches from a fixed location. Human beings and sensitive electronic equipment can withstand the acceleration of the vehicle. This subsystem provides a means of getting required supplies (sensitive electronics) in space. It also adds a degree of flexibility due to man's potential presence in space. The NASA shuttle is an example of a FLG launch system.

Mobile Low-G (MLG) launch system: Similar to an FLG except the launch site is not geographically fixed. Therefore, this subsystem adds a degree of survivability due to the mobile launch location. The Trans-Atmospheric Vehicle (TAV) under study (Covault, 1985) could be such a system.

Mass from orbit to satellite (Service systems)

Orbital Servicing Vehicle (OSV): A spacecraft, either manned or unmanned, designed to change orbit altitudes and inclinations in order to deliver mass to satellites requiring service. Once at the satellite, men or robots aboard the craft will perform the necessary servicing functions to the satellite. Man's presence adds flexibility while robots decrease flexibility. The costs to operate robots is envisioned to be less than a manned system because a robotic system does not have costs associated with life support. Potential concepts under study by NASA include the Orbital Maneuvering Vehicle or OMV (NASA, 1985) and the Orbital Transfer Vehicle or OTV ("Aerospace", 1982).

Space Base (SB): An Earth orbiting structure incapable of autonomous major changes in orbit. However it has station keeping propulsion to maintain a fixed earth orbit for long periods of time. This structure may be manned or unmanned and is capable of long term storage of satellite supplies. It also can act as a repair hanger for the OSV and satellites. This subsystem adds flexibility by providing supplies (and possibly man) in space where they are immediately available when needed. This would in general improve response times. NASA is reviewing concepts for a Space Station (NASA, 1984b).

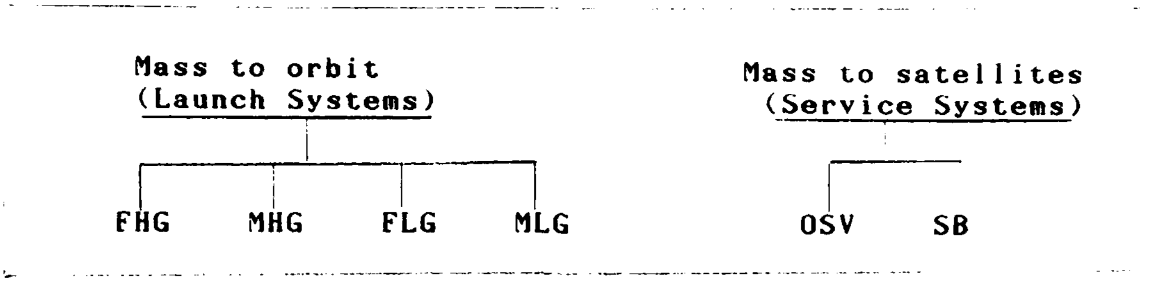


Figure 4.1 SSS Subsystem Options

With the above subsystem definitions different architectures for a SSS can be easily described through various combinations of launch and service systems. However, not all the resulting 45 possible system architectures shown in Table 4.1 are realistic.

4.2.2 Analysis to Identify Feasible SSS Architectures. Since it is assumed that replacement equipment for satellites is composed of sensitive electronics, then those systems having only an FHG or MHG as the sole launch system are not considered. It seems unlikely that a launch system designed for mobility can also be designed to withstand loads from a high-G launch. Additionally, such a system would require a large portable power supply to achieve the desired acceleration. Such physical realizations seem unlikely, therefore, the architectures using MHG launch systems are also not considered.

Table 4.1

List of 45 Systems

OSV+SB+MLG+MHG+FLG+FHG	OSV+SB+MLG+MHG	SB+MLG+MHG
OSV+MLG+MHG+FLG+FHG	OSV+SB+MLG+FHG	SB+MLG+FHG
SB+MLG+MLG+FLG+FHG	OSV+SB+MLG+FLG	SB+MLG+FLG
OSV+SB+MLG+MHG+FHG	OSV+SB+MHG+FLG	SB+MHG+FLG
OSV+SB+MLG+MHG+FLG	OSV+SB+MHG+FHG	SB+MHG+FHG
OSV+SB+MHG+FLG+FHG	OSV+SB+FLG+FHG	SB+FLG+FHG
OSV+SB+MLG+FLG+FHG	OSV+MLG+MHG	OSV+SB+MHG
OSV+MLG+MHG+FLG	OSV+MLG+FHG	OSV+MHG
OSV+MLG+MHG+FHG	OSV+MLG+FHG	OSV+FHG
OSV+MLG+FLG+FHG	OSV+MHG+FLG	OSV+MLG
OSV+MHG+FLG+FHG	OSV+MHG+FHG	OSV+FLG
SB+MLG+MHG+FLG	OSV+FLG+FHG	SB+FLG
SB+MLG+MHG+FHG	OSV+SB+MLG	SB+MHG
SB+MLG+FLG+FHG	OSV+SB+FLG	SB+FHG
SB+MHG+FLG+FHG	OSV+SB+FHG	SB+MLG

Finally, it is assumed that future satellite designs would not include major orbit changing capabilities since there is a heavy cost penalty in terms of launch weight and design complexity when including a propulsion/guidance pack on each satellite. In future satellites configured as functional modules attached to a common platform, if one module needs servicing it is unlikely that the platform will be moved to a SB (for servicing) because that would mean taking

the functioning modules "off-line". Several cost studies done for NASA indicate that on-orbit servicing is desirable (Heald, 1981) and that a servicing vehicle is an integral part of the system. Therefore, those systems/architectures that are comprised of an SB and launch system only (no OSV) are eliminated. Table 4.2 lists the resulting 12 feasible systems and the key assumptions made in selecting them.

Table 4.2

Feasible SSS Configurations with Assumptions

Feasible SSS		
FLG+OSV	FHG+MLG+OSV	FHG+FLG+SB+OSV
MLG+OSV	FLG+SB+OSV	FLG+MLG+SB+OSV
FHG+FLG+OSV	MLG+SB+OSV	FHG+MLG+SB+OSV
FLG+MLG+OSV	FLG+MLG+FHG+OSV	FHG+FLG+MLG+SB+OSV

Assumptions

. Mobile high-G launch is not feasible.

. Satellite supplies will include sensitive electronics requiring low-G launch.

. Once placed in orbit, satellites will not be capable of autonomous orbit changes.

This reduction of 45 possible system architectures to 12 feasible systems demonstrates how one may take into account the environment and bounds of the problem into the modeling process. Such simplifications are often needed to avoid including unnecessary information in the model and thus better focus the efforts of the analyst.

4.2.3 Selecting Four SSS for Equation Development. To reduce the focus for detail modeling a smaller number of candidate systems is selected from the set of 12 which on a gross level best achieves each of the objectives. In this approach the systems are qualitatively rank ordered in each objective. The concept of Pareto optimality (to be described later) is used on this ranking to identify those SSS configurations which are non-dominated. This reduced set of configurations will be studied in more detail for equation development.

The approach used to generate the qualitative rankings is a novel application of Interpretive Structural Modeling (ISM). Under certain conditions ISM can be used to form a hierarchy tree with the feasible systems at various levels of the tree. The hierarchy is interpreted as a rank ordering of the systems. A cursory description of ISM is now presented before discussing the results of its application to the 12 feasible SSS configurations.

4.2.3.1 Interpretive Structural Modeling (Sage, 1977:Ch 4). The complexity of systems exists because of the large number of elements (components) and the different types of interactions between those elements. These elements and interactions take on various forms. They may be components of a mechanical system, or in another form, theoretical concepts tied together to establish a hypothesis in an individual's mind.

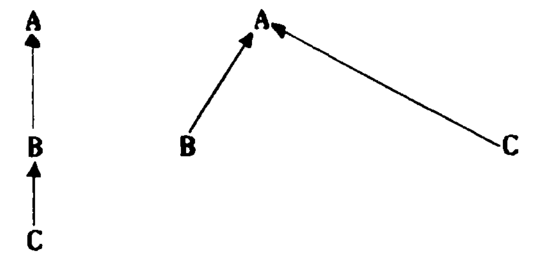
In any form, complex systems have a characteristic called "structure." Sometimes this structure is obvious, such as in a managerial organization in a corporation, or at times it is less obvious, such as the value system of a decision maker. In the physical sciences, structure is articulated through mathematics, whereas in the social sciences, articulation of structure is not done in such a clear fashion. Whether articulated or not, an analyst must deal with the structure of a complex system when attempting to describe it. A well defined structure is an invaluable aid to forming a clear description of the system which also can assist a decision maker to make better decisions about the system.

A common approach to represent and define structure is through the use of graphs. For example, a chart of the managerial organization in a corporation is such a representation. One way to transform unclear, poorly articulated mental models of systems into visible, well defined graphical models is through interpretive structural modeling or ISM. This process has its basis in mathematics, particularly in graph theory, set theory, mathematical logic, and matrix theory. Specifically, the term ISM refers to the "systematic iterative application of graph theory notions such that there results a directed graph (digraph) representation of complex patterns of a particular contextual relationship among a set of elements."

Digraphs conveniently show how elements interact in terms of the chosen relationship. They communicate that information at a glance. Consider the two digraphs shown in Figure 4.2 using the relation "costs less than".

Elements: Hypothetical Set

Relation: Costs less than



(a) (b)

Figure 4.2 Sample Digraphs

The elements A, B, and C represent physical items of interest. Digraph (a) shows that C costs less than B which is less than A. While digraph (b) indicates that both items B and C cost less than A, the costs of B and C are not distinguishable. The directed line lengths have no meaning as a measure of strength or distance. They simply represent existence of a relation. One important point is that a digraph is unique for the relationship it represents. If the chosen relation was instead "is larger than", a different digraph could occur with A, B, and C on entirely different levels. Therefore, a digraph should not be interpreted for relations other than the one used to form it.

For complex systems, such graphs are many times difficult to envision a priori by just looking at the whole set without a systematic method. However, the interaction between two elements is easier to identify. Thus the underlying principle in ISM is to examine interactions between each pair of elements within a system and combine the results to define the system structure. Prior to using ISM an analyst must then establish the following two primitives: (1) the element set and (2) a binary contextual relation. It will be through applying the contextual relation to pairs of elements that the system structure will be defined. An example comparison might be "element I is preferred to element J". Let pi represent the i th element of the element set P, and R represent the contextual relation. The notation $p_i R p_j$ will be used to mean that element p_i is related to element p_j by the relation R, and $p_i !R p_j$ will be used to mean p_i is not related to p_j by R.

The results of the pairwise comparisons are recorded in matrix form. The rows of the array represent the "I" elements and the columns represent the "J" elements. Thus a 100 element system is represented by a 100 by 100 matrix. The entries in the matrix are determined by one of four responses to the pairwise comparison. If the relationship holds from element I to element J and not in both directions ($p_i R p_j$ and $p_j !R p_i$) the (i,j) entry is a 1 and the (j,i) entry is a 0. But if the relationship holds (in the other

direction) from element J to element I and not in both directions ($p_j R p_i$ and $p_i !R p_j$) then the (j,i) entry is a 1 and the (i,j) entry is a 0. If the relationship holds in both directions ($p_i R p_j$ and $p_j R p_i$) then both the (i,j) and (j,i) entries become 1. Finally, if the relationship does not hold in either direction ($p_i !R p_j$ and $p_j !R p_i$) then both (i,j) and (j,i) become 0. The remaining entries along the diagonal become 0 because by definition a digraph contains no loops ($p_i !R p_i$ for all p_i in P). After the matrix entries are identified the next step is to form a digraph using this information.

A fundamental characteristic of a digraph is that elements are grouped in "levels." Consider a particular element p_i and how it relates in terms of the chosen relation to the other elements of set P. There is a set of elements $L(p_i)$ such that $p_i R p_k$ and $p_k !R p_i$ for each element p_k in $L(p_i)$. This set is called the lift set of element p_i and does not contain p_i. Another set of elements $D(p_i)$ contains elements p_k such that $p_k R p_i$ and $p_i !R p_k$ for each element p_k. This set is called the drop set and does not contain p_i. The remaining set of elements not in either $L(p_i)$ or $D(p_i)$ are part of the vacancy set $V(p_i)$ associated with p_i. Thus the relations between p_i and the other elements of P are conveniently structured into levels as shown in Figure 4.3.

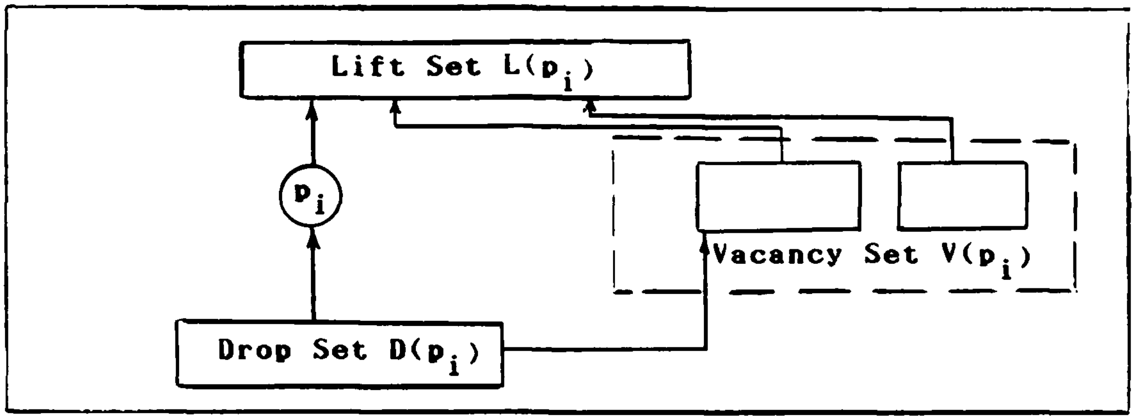


Figure 4.3 Structural Model of $L(p_i)$, $D(p_i)$ and $V(p_i)$

Each of the three sets can be associated with a position in the digraph. $L(p_i)$ will appear on levels higher than p_i, $D(p_i)$ will appear on levels lower than p_i, and $V(p_i)$ appear in unconnected sections (probably on similar levels). Notice that the top elements in a digraph have no L( ) and the bottom elements have no D( ). The levels can then be found by identifying the top set of elements as those with no L( ), putting them on Level one, setting them aside, then identifying the top set of the remaining elements, putting them on Level two, setting them aside, and continuing until all elements are assigned a level.

The mathematical techniques used to perform this partitioning for every element and combine the results are too extensive to present here (refer to Sage, 1977: 119-128). After elements are identified with levels of the system digraph the directed lines that represent the relationship between elements are identified from the entries in the matrix. An entry of 1 in the (i,j) position represents a

directed line running from element I to element J. A graph using all these lines is correct, but unneccesarilly confusing. If the relation R is transitve, many of the directed lines have redundant meaning and can be removed.

A relation is transitive if element I is related to element J and element J is related to element K necessarily implies that element I is related to element K. For example, the relations "I is larger than J" and "I is more expensive than J" are transitive. Because of the "one way" nature of transitive relations, the ISM generated digraph representing a transitive relation cannot have cycles or feedback loops as demonstrated in Figure 4.4.

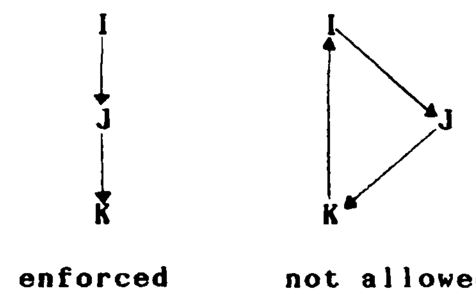


Figure 4.4 Transitive Digraphs (Briggs, 1985)

To summarize, interpretive strucural modeling provides a means to transform an unclear mental model into a graphical representation of structure. This structure is unique for the relationship used to generate it. The directed lines of the digraphs have no meaning other than "the relationship exists." Therefore, the "distance" between levels cannot be determined. However, this forming of levels can

be interpreted as a rank ordering of the elements if the relationship used is transitive and all elements form a single digraph. This ranking interpretation of ISM digraphs is used in this study and will now be demonstrated.

4.2.3.2 Pairwise Comparisons of 12 Feasible SSS. To apply the previously described ISM techniques to rank the 12 feasible systems, the systems are treated as elements and the seven objectives are used to develop the contextual relationships for pairwise comparisons. For instance, word relationships like "the MLG+OSV+SB system has higher operating costs than the MLG+OSV system" are used. The seven contextual relationships intended for use are shown in Table 4.3. Notice that they are all transitive relations.

Table 4.3

Contextual Relationships for System Pairwise Comparisons

1. System I "has higher operating costs than" system J.
2. System I "has higher initial costs than" system J.
3. System I "delivers less mass to the satellites than" system J.
4. System I "has lower survivability than" system J.
5. System I "is less flexible than" system J.
6. System I "is less reliable than" system J.
7. System I "improves satellite performance less than" system J.

Table 4.4

Full Word Equations for Contextual Relationships

1. Operating Cost = F(Mission Dependant Costs)
   + F(Mission Independant Costs)

   F(Mission Dependant) = F(Mission Fuel Costs)
   + F(Mission Required Parts)

   F(Mission Fuel Costs) = F(# of Satellites)
   + F(Subsystem Propulsion Methods)
   + F(Satellite Orbit)

   F(Mission Independant) = F(Maintenance) + F(Non-mission Fuel) + F(Overhead)
   + F(Personnel)

2. Initial Costs = F(R&D) + F(Purchase) + F(Deployment)

   F(R&D) = F(# of Subsystem Types to Develop) + F(New Technology Required) + F(Complexity of Subsystem to Develop)

   F(Purchase) = F(# of Subsystem Units)
   + F(Size and Weight of Each Unit)
   + F(Complexity of Subsystem)

   F(Deployment) = F(# of Subsystem Units to Deploy)
   + F(Size and Weight of Each Unit)
   + F(Unit Deployed Orbit)

3. Mass Delivered to Satellites = F(# of Subsystem Units)
   + F(Launch Vehicle Payload Capacity)
   + F(Delivery Rate of Launch Vehicle)
   + F(Service Vehicle Payload Capacity)
   + F(Delivery Rate of Service Vehicle)

4. Survivability = F(# of Subsystem Units)
   + F(Abiliy to Avoid Hostile Action)

5. Flexibility = F(Ability to Deal with Unplanned Maint.)
   + F(Ability to Accomodate Changes)

6. Reliability = F(# of Parallel Subsystems)

7. Satellite Performance Improvement = F(Increased Satellite Availability) + F(Increased Satellite Dependability) + F(Ability to Upgrade Satellite)

Due to the varying types and numbers of subsystems comprising each system, it is not immediately obvious how some of the word relationships hold. Therefore, the word equations shown in Table 4.4. are formulated to initially identify factors or functions (indicated by F(words)) of a SSS that contribute to achieving each objective. These in essence define the models and establish the gross level of detail used for the pairwise comparisons (remember the reason for doing the comparisons is to reduce quickly the number of SSS to be modeled). However, to use some of the factors would require more detailed system models. For instance, under operating costs, the magnitude of the effect of mission required parts, subsystem propulsion methods, number of satellites, and orbits of the satellites can not be determined for each SSS at this level of detail. In fact, factors are not used that require knowledge of a physical realization of a subsystem. Thus, the comparison of mass delivered to satellites is non-discriminant between systems because it requires knowledge about the payload capacity and usage rate of each subsystem. Similar knowledge requirements preclude the comparisons using initial costs and satellite performance improvement. Therefore, all systems are assumed to be comparable in initial costs, mass delivered to sattelites, and satellite performance improvement.

The remaining contextual relations associated with the objectives of low operating costs, high survivability, high flexibility, and high reliability are used for the actual pairwise comparisons. The factors used to determine the results of these comparisons are shown in Table 4.5.

Table 4.5

Reduced Word Equations for Contextual Relationships

1. Operating Cost = F(Mission Fuel Costs) + F(Maintenance) + F(Non-mission Fuel) + F(Overhead) + F(Personnel)

2. Survivability = F(# of Subsystem Units) + F(Abiliy to Avoid Hostile Action)

3. Flexibility = F(Ability to Deal with Unplanned Maint.) + F(Ability to Accomodate Changes)

4. Reliability = F(# of Parallel Subsystems)

Of these remaining factors, some are easy to compare on a system level when the two SSS are vastly different. For instance, a SSS composed of one launch system and one service system is less reliable than one made of all five subsystems because of the multiple number of launch systems in the second SSS. But when the number and types of subsystems are similar, then the individual subsystems must be compared to determine how the relationship applies to the whole system. To be consistent, the assumptions shown in Table 4.6 were established prior to performing the comparisons.

Table 4.6

Assumptions for Pairwise Comparisons

- Operating Costs

  Mission Fuel: MLG < FLG
  FHG < MLG

  Maintenance: MLG < FLG

  Overhead: MLG = FLG
  MLG > SB
  SB = FHG

  Personnel: MLG = FLG
  SB = FHG

- Survivability

  Mobile launch systems > Fixed launch systems

  Increases with number of subsystems (fewer choke points, single point failure concept)

- Flexibility

  Mobile launch systems > Fixed launch systems

  Increases with type and number of subsytems

- Reliability

  Increases with type and number of subsytems

- At this level of detail, Initial Costs, Mass Delivered to Satellites, and Satellite Performance Improvement are considered comparable between SSS.

To demonstrate the logic used, consider the eleven pairwise comparisons (in terms of operating costs) between the FLG+OSV system and each of the other systems. The results are shown in Table 4.7.

Table 4.7

Sample Results of Pairwise Comparisons

System I	Operating Costs Factors					System J
	mission fuel	maint	non-mission fuel	over-head	person-nel	
FLG+OSV	>	>	=	=	=	MLG+OSV*
" TIE	>	=	=	<	<W	FHG+FLG+OSV
" *	>	=	=	<	<W	FLG+MLG+OSV
" *	>	<	=	<	<	FHG+MLG+OSV
" *	>	<	=	<<	<<	FLG+MLG+FHG+OSV
" *	>	<	<	<	<	FLG+SB+OSV
" *	>	=	<	<	=	MLG+SB+OSV
" *	>	<	<	<	=	FHG+FLG+SB+OSV
" *	>	<	<	<	<	FLG+MLG+SB+OSV
" *	>	=	<	<W	=	FHG+MLG+SB+OSV
" *	>	<	<	<	<	FHG+FLG+MLG+SB +OSV

Notes:
= = "I" has about the same (ops cost factor) as "J"
> = "I" has greater (ops cost factor) than "J"
< = "I" has less (ops cost factor) than "J"
>W = "I" has slightly greater (ops cost factor) than "J"
<W = "I" has slightly less (ops cost factor) than "J"
>> = "I" has much greater (ops cost factor) than "J"
<< = "I" has much less (ops cost factor) than "J"
* = marks system that is considered having the lower operating costs between systems I and J.

Two systems are compared in terms of each of the five operating costs factors of mission fuel, maintenance, non-mission fuel, overhead, and personnel. The response is recorded under the appropriate column using arrows to point

to the lower costing system, or an equal sign to indicate comparable costs. Additionally, the arrows indicate the strength of the cost difference by the following convention: a 'W' to the right of the arrow indicates a weak difference, a single arrow indicates a nominal difference, and a double arrow is a strong difference. The aggregate of these responses determines which of the two systems is identified to have lower operating costs. This system is marked with an asterisk, and if neither system is identified then the word TIE is placed in the System I column. For instance, consider the first comparison. Since the OSV is common to both systems, it is not a discriminator in any factor (this is true in all SSS pairwise comparisons). Invoking the assumptions of Table 4.6, the MLG+OSV system is lower in the operating cost factors of mission fuel and maintenance, and neither system is lower in the other three factors. Therefore, the MLG+OSV system is identified as having lower operating costs than the FLG+OSV system. Thus, the statement "the FLG+OSV system has higher operating costs than the MLG+OSV system" is true.

An interactive computer program is used to enter the results of the pairwise comparisons of Operating Costs, Survivability, Flexibility, and Reliability and then perform the subsequent matrix "partitioning" referred to in the previous section describing interpretive stuctural modeling (ISM). The output identifies the level number of each sys-

tem in the ISM digraph (hierarchy tree) representing the relationship chosen. Figure 4.5 shows the digraph for the relation "lower operating costs".

Elements: 12 Feasible SSS (A through L)

Relation: Lower Operating Costs

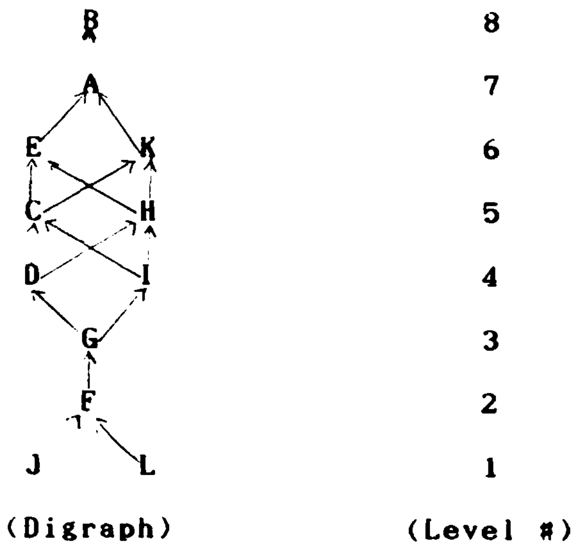


Figure 4.5 Operating Costs Digraph with Level #'s

Table 4.8 shows a listing of the 12 feasible systems and the number of their associated level in each of the four ISM digraphs. These level numbers represent the order of the ranking but do not indicate relative strength of objective achievement. For instance, under operating costs, becuase system G is on level 3 it is less costly than system L on level 1. However, this does not necessarily indicate that system G is one third as costly as system L. These numbers are then treated as performance measures or indicies (PIs) to be used in applying the concept of Pareto optimality or non-dominance.

Table 4.8

Ranking of SSS by PIs

SYSTEM	OP COST	IN COST	MASS DEL	SURVIVAB	FLEXIBIL	RELIABIL	SAT PERF
A. FLG+OSV	7			1	1	1	
B. MLG+OSV	8			3	2	1	
C. FHG+FLG+OSV	5			2	2	2	
D. FLG+MLG+OSV	4			4	3	2	
E. FHG+MLG+OSV	6			4	4	2	
F. FLG+MLG+FHG+OSV	2			5	5	3	
G. FLG+SB+OSV	3			2	3	2	
H. MLG+SB+OSV	5			4	6	2	
I. FHG+FLG+SB+OSV	4			3	4	3	
J. FLG+MLG+SB+OSV	1			5	7	3	
K. FHG+MLG+SB+OSV	6			5	8	3	
L. FHG+FLG+MLG+SB+OSV	1			6	9	4	

Notes: - 1 indicates lowest achievement of objective
- Numbers are for comparison within columns only, not between them.
- Numbers for Initial Costs, Mass Delivered to Satellites, and Satellite Performance Improvement are not shown for figure clarity (assumed equal for all SSS).

4.2.3.3 Selecting 4 SSS to Model. Next the concept of Pareto optimality (Changkong and Haimes,1983:114)is used to identify a non-dominated solution set (NDSS) of candidate systems. The vectors of PIs for all systems are compared in a pairwise manner. A system is considered dominated by anocher system if at least one performance measure of the second system is strictly better than, and the remaining

performance measures of the second system are at least equal to (never less than) those of the first system. The dominated systems are removed and the remaining systems form the NDSS. For example consider the five system set shown in Figure 4.6. The FHG+MLG+SB+OSV system is a non-dominated solution because none of the bracketed systems dominate it. In fact, when the other seven systems are included in the set, the FHG+MLG+SB+OSV system is still a member of the NDSS.

SYSTEM	OP COST	IN COST	MASS DEL	SURVIVAB	FLEXIBIL	RELIABIL	SAT PERF
FLG+SB+OSV	3			2	3	2	
MLG+SB+OSV	5			4	6	2	
FHG+FLG+SB+OSV	4			3	4	3	
FLG+MLG+SB+OSV	1			5	7	3	
FHG+MLG+SB+OSV	6			5	8	3	

non-dominated solution

Figure 4.6 Non-Dominated Solution Example

The NDSS for the 12 feasible systems consisted of three systems. They contained two, four, and five subsystems. It is felt that an additional system made of three subsytems would better represent the span of the 12 feasible systems. The ranked values of the chosen system (FHG+MLG+OSV) are in the middle range of the rankings. The boxed systems in

Figure 4.7 are the selected four systems to be further modeled.

SYSTEM	OP COST	IN COST	MASS DEL	SURVIVAB	FLEXIBIL	RELIABIL	SAT PERF
FLG+OSV	7			1	1	1	
MLG+OSV *	8			3	2	1	
FHG+FLG+OSV	5			2	2	2	
FLG+MLG+OSV	4			4	3	2	
FHG+MLG+OSV **	6			4	4	2	
FLG+MLG+FHG+OSV	2			5	5	3	
FLG+SB+OSV	3			2	3	2	
MLG+SB+OSV	5			4	6	2	
FHG+FLG+SB+OSV	4			3	4	3	
FLG+MLG+SB+OSV	1			5	7	3	
FHG+MLG+SB+OSV *	6			5	8	3	
FHG+FLG+MLG+SB+OSV *	1			6	9	4	

NOTE: *Non-dominated solution
**Dominated solution retained to represent SSS made of 3 subsystems

Figure 4.7 Final Four

This section presented the qualitative (first order) modeling and analysis processes used to select representative systems for equation development. To quickly reduce the number of candidates, simplifying assumptions were made to emphasize the differences among the systems. The following section will describe the analytical model equations representing the selected systems. The analysis of one of these models is the subject of Chapter V.

4.3 Analytical Models

Following completion of modeling at a conceptual or qualitative level, equations can be developed to form analytical models that represent an increased level of detail. These analytical (quantitative) models describe the real-world behavior of a system and are valid to the extent that the equations represent the conditions or limits defined by the environment. The form of the model equations must be such that the analyst can differentiate between candidate designs and predict the relative merits of each. The statespace model form meets these criteria (DeWispelare, 1984) and is used in this study. A description of the general statespace model form will be presented in section 4.3.1. This is followed by a discussion in section 4.3.2 about the general characteristics of a Satellite Servicing System (SSS). It includes how the characteristics are incorporated into the equations used to model system and subsystem interrelationships within the potential models.

At the level of detail achieved by the model equations, no differentiation between the MLG and the FLG launch systems could be identified. Therefore, the terms MLG and FLG will be deleted and the simple term low-G (LG) launch system will be used for the rest of the analytical model discussions. This results in two of the potential SSS systems identified in the previous section (the SB+FHG+MLG+OSV system and the SB+FHG+MLG+FLG+OSV system) collapsing into the

SB+FHG+LG+OSV system. The three potential SSS systems are now the LG+OSV, FHG+LG+OSV, and the SB+FHG+LG+OSV systems.

4.3.1 Statespace System Modeling (Clark and DeWispelare, 1985). A statespace model is a mathematical description of a system. For a linear model the equations are normally grouped in matrix form as shown:

$$\underline{Z} = A\underline{X} + B\underline{U}' + \underline{K}_1 \tag{4.1}$$

$$\underline{X} = C\underline{X} + D\underline{U}' + \underline{K}_2 \tag{4.2}$$

$$\underline{L}_x \leq \underline{X} \leq \underline{U}_x \tag{4.3}$$

$$\underline{L}_{u'} \leq \underline{U}' \leq \underline{U}_{u'} \tag{4.4}$$

where $\underline{Z}$ is an px1 vector of performance indices(PI's), $\underline{X}$ is an nx1 vector of state variables, $\underline{U}'$ is an mx1 vector of control variables, $\underline{K}_1$ and $\underline{K}_2$ are constant vectors of dimension px1 and nx1 respectively, and $\underline{L}_x$ and $\underline{L}_{u'}$ are vectors of lower bounds and $\underline{U}_x$ and $\underline{U}_{u'}$ are vectors of upper bounds for the system variables. A, B, C, and D are matrices that form the system equations. Even though the above equations suggest a linear form, a general statespace model is not restricted to equations that are linear in $\underline{X}$ and $\underline{U}$.

For this study the system equations are nonlinear and can be represented in the following form:

$$\underline{Z} = f(\underline{X}, \underline{U}) \tag{4.5}$$

$$\underline{X} = g(\underline{X}, \underline{U}) \tag{4.6}$$

$$\underline{L}_x(\underline{X}, \underline{U}) \leq \underline{X} \leq \underline{U}_x(\underline{X}, \underline{U}) \tag{4.7}$$

where $\underline{Z}$ is a px1 vector of PI's, $\underline{X}$ is a nx1 vector of state variables, and $\underline{U}$ is a kx1 vector of exogenous variables. The exogenous variables include the previously mentioned control variables, $\underline{U}'$, and constant vectors ($\underline{K}_1$ and $\underline{K}_2$). The functions f(...) and g(.,.) represent nonlinear relations between the PI's and the state and exogenous variables. $\underline{L}_x(\ldots)$ and $\underline{U}_x(\ldots)$ are functions of the state and exogenous variables that generate vectors of lower and upper bounds on the state variables.

Hereafter Eqs (4.5), (4.6) and (4.7) will be referred to as the performance indice (PI) equations, state (equality) equations, and constraint (inequality) equations, respectively. The state and constraint equations can be thought of as representing the physical model; while Eq (4.5) represents the performance measure of the physical system (ie the PI model). Notice that all the equations are functions of state variables which describe the system being modelled, and exogenous variables which describe the environmental or external conditions to which the model is subjected.

The state variables in the column vector $\underline{X}$ are system discriptors. These variables are parameters used to describe a given system and distinguish it from similar systems; possible choices include the size and number of each subsystem, payload mass, and the number of crew members required. An analyst (designer) has a great deal of freedom

in choosing which system characteristics will be used as state variables. However, whether they are physical characteristics or convenient abstract mathematical descriptors, all state variables must meet two criteria:

1. A state variable must interrelate with another system variable or directly affect a performance index.

2. The feasible region of the state variable must be large enough to allow distinctly different realizatons of the variable.

The first restriction is important because the candidate systems are judged in terms of the performance measures. Therefore, a state variable must directly or indirectly contribute to the PI values. As a counter example, consider using the color of a vehicle as a state variable. While color is a valid descriptor, it will not contribute to achieving such design objectives as increased payload capacity or smoother ride.

The second restriction is to ensure that the state variables do in fact provide a mechanism to distinguish between candidate solutions. If the feasible region defined by the constraints is too small to meet the second state variable criterion, then the system characteristic is essentially fixed and becomes a required design parameter.

Exogenous variables are similar, but not identical, to control variables in the linear form. In the linear case control variables are those input variables which "drive" the state variables to a given configuration. For instance,

in a preliminary missile design study (Clark and DeWispelare, 1985b), cruise velocity is a control variable. To achieve a given cruise velocity, the propulsion system must produce some threshold thrust relative to the total drag of the missile. Therefore, the state variable thrust and the state variables directly related to drag are forced via a state equation by the control variable cruise velocity to an appropriate configuration which allows the required cruise velocity to be acheived.

In the non-linear statespace form the exogenous variables are defined as those variables (usually set to constant values) that represent the effects of the environment on the system being modeled. These include control variables and other constant variables that affect system operation and performance. Not only can exogenous variables act as inputs to the model, such as the number of satellites and their required service interval, they can also represent bounds on the state variables, such as minimum and maximum time between LG launches at one site.

The state equations represent relations between the state and exogenous variables. For this study these equations represent the relations that exist between the different subsystems of a SSS, or the relationships between internal states of an individual subsystem. As one state variable changes value, other variables will also change value to satisfy the state and constraint equations.

The constraint equations represent limits on both the values and functions or interactions that state variables can attain. These constraints usually represent the technological or physical limitations on the system. The realizable values of the state variables form the feasible region of the statespace.

The PI equations represent the response of the system as the variables (X and sometimes U) are varied over the feasible region of interest. In other words, the PI's measure the model performance level for a given realization (state) of the system and provide criteria to select the best system. The PI values, Z, are generated from equations containing state and exogenous variables combined in such a way as to yield a measure of achievement of the design objectives.

Figure 4.8 graphically depicts the interactions of the system variables (X and U) with the physical and PI models. A given candidate SSS, represented by a realization of state vector X', is checked for feasibility by the physical model. If the physical model equations are satisfied, then the state vector, X', is feasible and redesignated as X. This vector (X) is then used to calculate the level of performance for the candidate SSS.

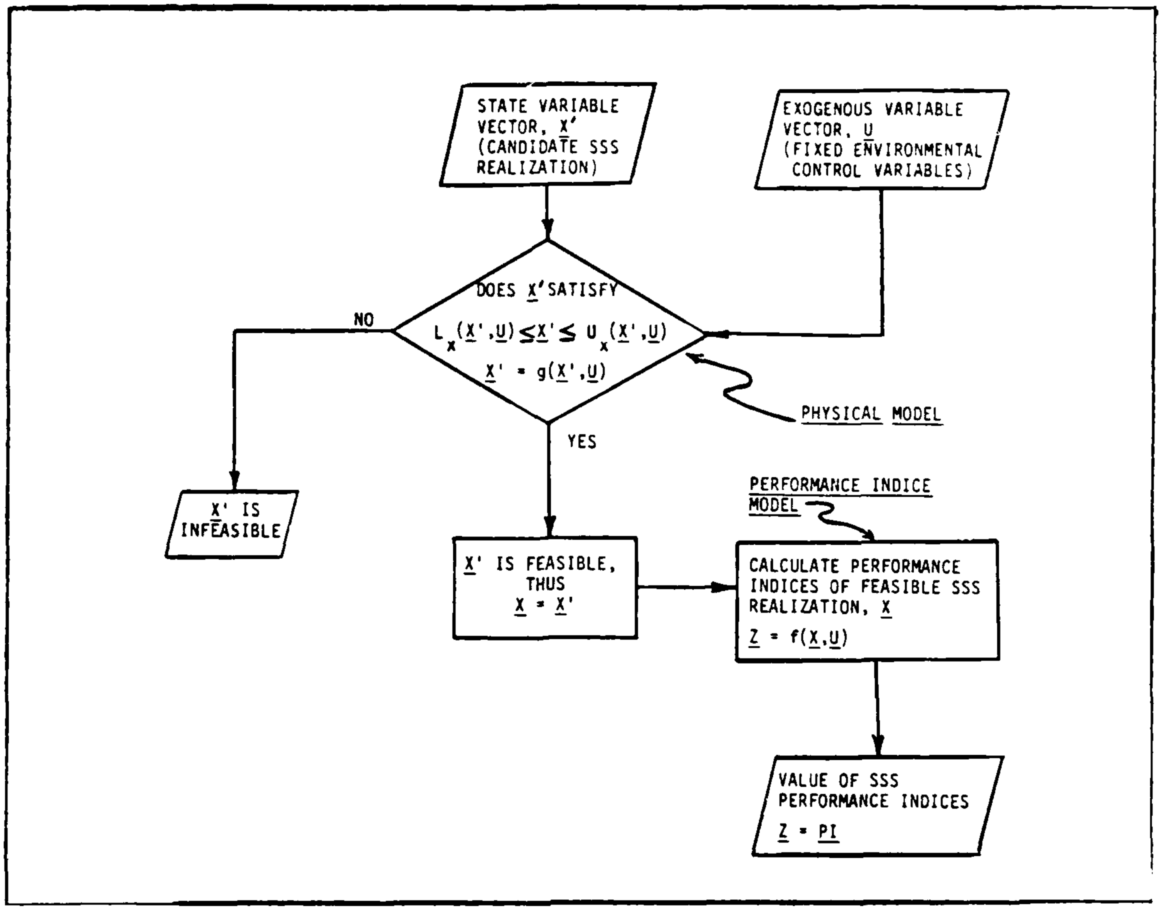


Figure 4.8 Non-Linear Statespace Model Diagram

Once the system model equations have been cast into a statespace form multi-objective optimization theory (MOOT) techniques can be applied to solve for optimal system realizations. But before the MOOT process for this effort is discussed (see Chapter V), a qualitative discussion of the non-linear system equations is presented. It is not the purpose of the next section to give detailed derivations for each equation. Rather, the goal is to present the assumptions and system characteristics that the model equations represent.

4.3.2 Model Description. Due to the differences in each of the potential servicing systems, one comprehensive model for the three systems is not possible. Therefore, each system is modeled individually starting with the simplest system (LG+OSV) and building upon it to form the more complex systems. A detailed listing of the different model equations is in Appendix D, the model variables are in Appendix E, and the intermediate (algebraic simplification) equations are in Appendix F. References for all equations and variables can be found in the appendices listed above. For the readers convenience a listing of the state variables is in Table 4.9 and a listing of model constants (important exogenous variables) is in Table 4.10.

Table 4.9

Subsystem State Variables (SV)

SV	DESCRIPTION	UNITS	RANGE
	ORBITAL SERVICING VEHICLE		
X500	Number of OSV systems	number	0-inf
X501	# of OSV missions/time	#/hr	0-inf
X510	OSV Payload mass	kg	0-inf
X525	OSV stucture mass	kg	0-inf
X526	Mass of propulsion fuel	kg	0-inf
X545	OSV reliability	number	0-1
X555	OSV crew size(#-people)	number	0-inf
X560	Number of satelittes serviced per OSV mission	number	0-inf
X561	Mass delivered to a satellite per service	kg	0-inf
X565	Number of waiting orbits(n)	number	1-inf

Table 4.9 Continued

SV	DESCRIPTION	UNITS	RANGE
	LOW-G LAUNCHER		
X300	Number of LG systems	number	0-inf
X301	# LG missions/time	#/hr	0-inf
X310	Payload mass per launch	kg	0-inf
X320	Number of launch sites	number	0-inf
X325	Vehicle structure mass	kg	0-inf
X326	Mass of propulsion fuel	kg	0-inf
X330	LG downtime between missions	hr	168-inf
X335	Time between launches at a specific launch site	hr	24-8760
X345	LG reliability	number	0-1
X360	Rendezvous altitude	km	185-inf
X370	Number of LG stages	number	1-inf
	FIXED HIGH-G LAUNCHER		
X100	# FHG launches/time	number	0-inf
X110	FHG payload mass/launch	kg	0-inf
X120	Number of launch sites	number	0-inf
X135	Time between launches at a specific site	hr	24-inf
	SPACE BASE		
X400	# of space-bases	number	0-inf
X415	SB crew size (#people)	number	0-inf
X420	SB mass storage capacity	kg	0-inf
X425	SB structure mass	kg	0-inf

Table 4.10

Exogenous (Constant) Variables (U)

U	DESCRIPTION	UNITS	VALUE
	SATELLITE CONSTELLATION INPUTS		
U1	Average satellite altitude	km	800
U2	# of satellites	number	144
U6	Satellite service interval	yrs	3
U14	Percent of satellite required mass requirng low-G launch	%	25
	OSV Constant Inputs		
U18	Mass of OSV guidance equipment	kg	200
U19	OSV mass needs/mission	kg	100
U22	Cost/unit of OSV fuel	$/kg	0.32
U24	OSV isp	hr	0.14
	LG CONSTANT INPUTS		
U25	LG to OSV mass transfer rate	kg/hr	800
U26	OSV to Satellite transfer rate	kg/hr	400
U31	Cost/unit of LG fuel	$/kg	0.32
U33	LG ISP	hr	0.11
U35	LG to SB mass transfer rate	kg/hr	900
	PEOPLE RELATED INPUTS		
U75	SB life support requirements per person-time	kg	0.20
U76	OSV life support requirements per person-time	kg	0.64
U77	Maximum people time in space before rotation	weeks	13
U78	Cost/man-time	$/man-hr	1000
U79	Cost/man-year used in cost equations	$/man-yr	125000

Table 4.10 Continued

U	DESCRIPTION	UNITS	VALUE
	FHG CONSTANT INPUTS		
U111	Cost of earth based energy	$/watt-hr	0.00115
U114	Cost of FHG apogee fuel	$/kg	0.32
U121	Isp of apogee burn fuel	hr	0.09
	SB CONSTANT INPUTS		
U129	% of SB structure mass used for fuel calculation	%/yr	2
U130	SB safty level	month	1
U132	% of SB structure mass for parts calculation	%/yr	10
U133	SB structure mass to mass storage capacity ratio	none	1.0
U134	Cost of SB parts	$/kg	100
U138	SB deployment cost	$/kg	20000
U139	SB fuel cost	$/kg	0.32

The discussion that follows gives a description of the assumptions, ideas, and relationships expressed in the detailed model equations listed in Appendix D. All three models are discussed simultaneously; therefore, if a particular model of interest has a specific subsystem as a component, the discussion pertaining to that subsystem applies. For example, if the model of interest is the LG+OSV model, then the FHG and SB discussions do not apply. The detailed models in Appendix D start with a listing of equations applicable to all potential models, followed by three sections listing additional equations applicable to each specific model of interest.

4.3.2.1 <u>Operating Scenarios</u>. Many different SSS realizations are possible using the descriptions of the three candidate SSS from section 4.2. Potential operating scenarios are defined to assist in the model equation development, and help identify important relationships to be modeled. Therefore, the following scenario descriptions must be kept in mind when evaluating the validity of the equations.

Figure 4.9 displays a scenario for the LG+OSV system. In this scenario the LG is launched from Earth to a specific OSV rendezvous altitude (parking orbit). The OSVs are then refurbished and resupplied from the LG. The OSVs then depart on another servicing mission and the LG, emptied of payload, returns to Earth for refurbishment, resupply, and relaunch. In this model one LG could service several OSVs or multiple LGs could service a single OSV.

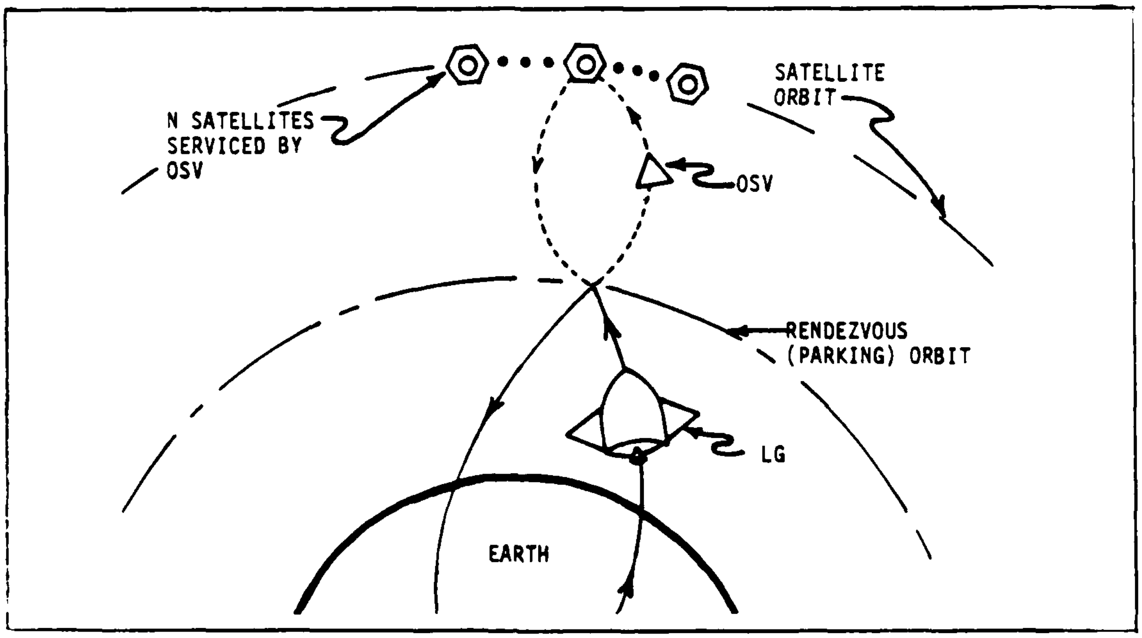


Figure 4.9 LG+OSV Operating Scenario

The FHG+LG+OSV operating scenario (Figure 4.10) is similiar to the LG+OSV operating scenario. The only difference is that the FHG vehicle is also launched into the LG+OSV rendezvous orbit and the OSVs are now resupplied from both LGs and FHGs. An important point to remember is that by definition the FHG can only carry mass that can withstand a high-G launch. Therefore, the LG must carry as a minimum all the mass that must be low-G launched.

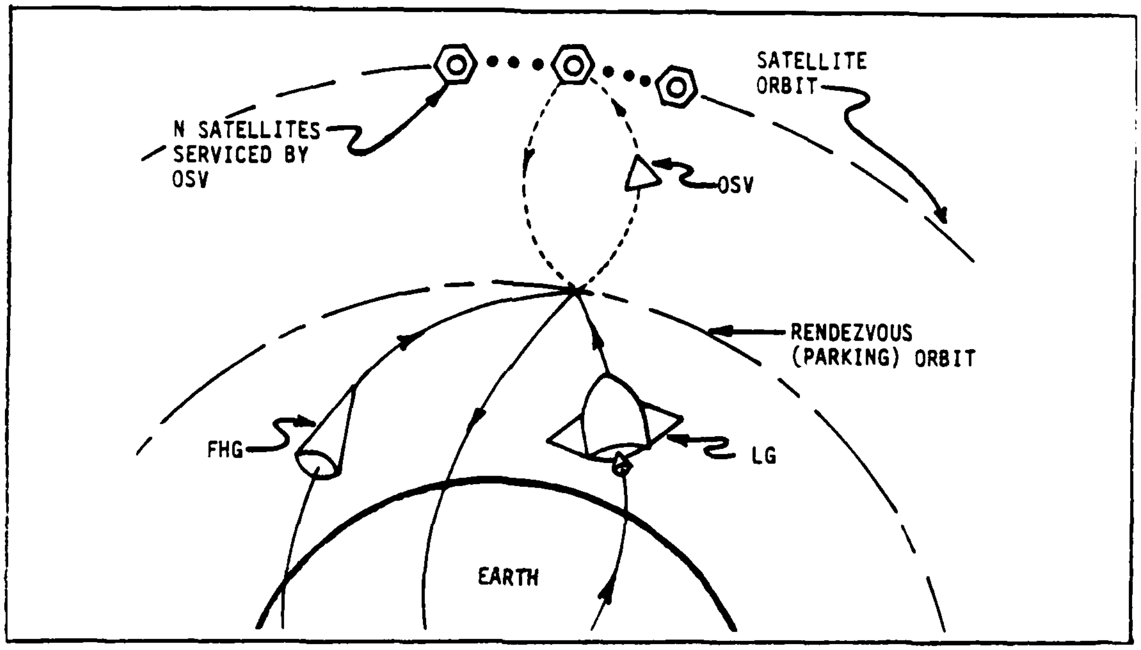


Figure 4.10 FHG+LG+OSV Operating Scenario

Figure 4.11 displays a possible SB+FHG+LG+OSV operating scenario. In this scenario all LGs and FHGs are launched to the SB orbit. The LGs transfer their entire payload to the SB and return to Earth for resupply, refurbishment, and relaunch. The FHG could be designed to rendezvous with the SB, or it could rendezvous with the OSVs and transfer the high-G payload directly to an OSV. The OSVs must link up

with the SB to pickup low-G launched parts. The SB is considered to be a mass storage facility and temporary personel quarters for OSV crew members arriving on the LG.

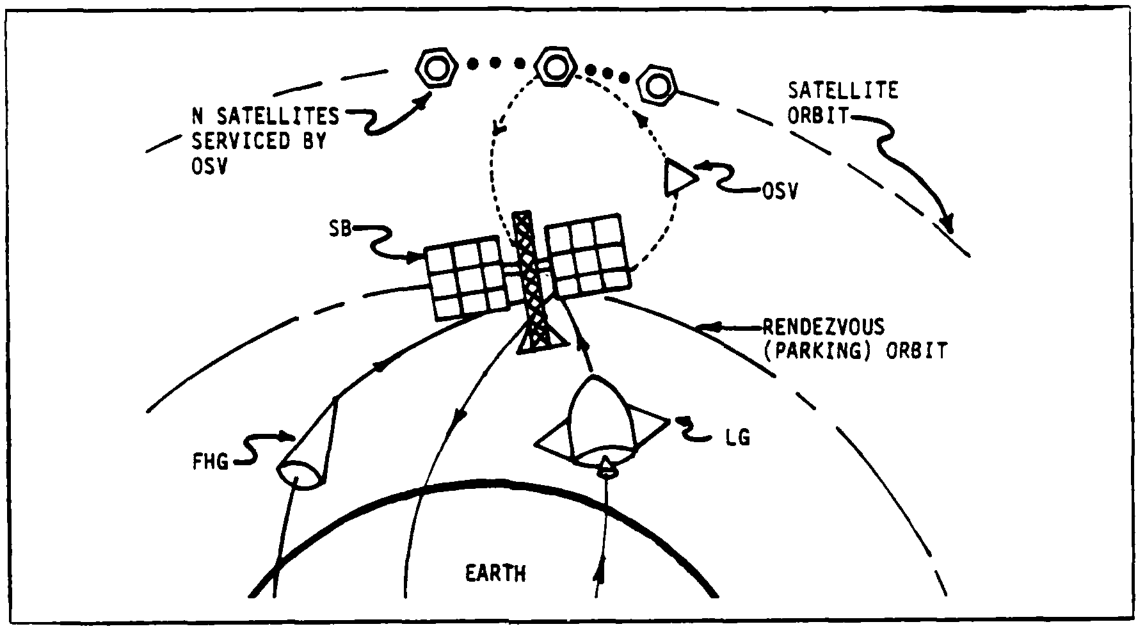


Figure 4.11 SB+FHG+LG+OSV Operating Scenario

4.3.2.2 Satellite Constellation. The amount of mass a SSS must deliver to orbit is driven by the satellite constellation being serviced. To represent this driving input the satellite model equations should take into account the different orbits and inclinations, the frequency of service, and the amount and kind of mass required by each satellite. However, the true nature of the satellite constellation(s) to be serviced by the SSS under study is not known. Therefore, rather than model the performance of a SSS to meet a specific demand, a Performance Index maximizing the actual mass deliverd by the SSS is modeled.

From this perspective, the delivery capability of different SSS configurations can be compared using a simple constellation. The benefit of using a simple constellation is that the orbital mechanics equations, describing how a servicing vehicle travels from satellite to satellite, are manageable (see Appendix G). These equations become increasingly complex with increasing number of orbits and inclinations. The impact of this simplification on the results will be discussed in section V. For this study, the satellite constellation consists of 144 satellites "# Satellites" (U2) equally spaced about one circular orbit at an altitude of 800km "Average Satellite Altitude" (U1) and zero degree inclination. All satellites will be given the same amount of mass "Mass delivered to a Satellite" (X561) at a fixed service interval "Satellite service interval" (U6). They will be serviced in a sequential order about their orbit. No on-demand servicing alternatives are considered.

4.3.2.3 Performance Index (PI) Equations Description. In order to adequately compare the different SSS models a common set of PI's must be defined. The PI's must measure the same characteristics in each model and should be understood by, and important to, the decision maker. In other words, the scalar value (PI) generated by the equations represents a level of achievement of the objectives (the seven identified previously) by a candidate SSS.

Flexibility, survivability, and satellite performance improvement objectives are not modeled. This is because no

two definitions of survivability and flexibility are identical. Survivability can mean how well the system avoids or deters hostile (man made) actions or its ability to avoid asteroids and space dust or space particles (natural hostile actions). Thus for the level of detail of this model, it is impossible to calculate a measure for survivability. Future, more detailed iterations should include this measure as a PI. Some of the inputs to this PI would be subsystem projectile avoidance (kinetic weapons), shielding thickness (meteroids, kinetic energy, and possibly laser weapons), and number of units in each subsystem.

The flexibility objective is subject to the same definition and inability to calculate a "number" as the survivability objective; therefore, flexibility is not calculated. Inputs to the flexibility measure in future iterations would probably include man's influence on the system and the ability of the system to perform different types and kinds of missions.

A measure of satellite performance improvement requires specific descriptions of the satellites serviced. As discussed earlier, these descriptions are not available; therefore, the satellite performance objective is not modeled. Future iterations should include this measure. The variables "average mass delivered to a satellite" (X561) and the time interval between services "Satellite service interval" (U6) should be important inputs to this PI.

Table 4.11

Performance Indicies

Z1	Operating Cost	Hourly Cost of Operating a SSS
Z2	Initial Cost	R&D, Production, and Deployment
Z3	Reliability	Ability to Perform a Mission
Z4	Mass Delivered	Mass Delivered Per Time

The four PI's modeled are shown in Table 4.11. The operating and initial costs are modeled for comparative purposes only and are not the total costs. Costs not included are assumed to be equal regardless of the number or types of subsystems. Costs regarded as equal would not add any meaningful information to the decision process; therefore, nothing would be gained by their calculation. If a specific cost was determined to not be equal for all systems, the new cost would have to be added to future iterations of this model.

Operating Cost:

Operating costs represent the costs of operating a SSS per hour. The costs are calculated assuming the SSS is fully operational and deployed. Table 4.12 shows the operational costs considered.

Table 4.12

Operating Cost Matrix

SSS Subsystem	Operating Costs Modeled				
	fuel	manpower	parts	launch site	other
OSV	x	x	s	n	s
LG	x	s	s	x	s
FHG	x	s	x	x	s
SB	x	x	x	n	s

note: x indicates cost included
s indicates the cost assumed the same all models
n indicates cost not applicable to subsystem

The costs which are designated with an "s" are costs which are approximately equal in each model. Examples of *costs not considered* are training, overhead personnel, technical system management, prelaunch checkouts, launch vehicle recovery and transportation, and cost of the mass delivered to the satellites. Costs designated by "n" are not applicable to the particular subsystem. The operating costs calculated are designated by "x" and are calculated in dollars per hour. Figure 4.12 identifies the subsystem state variables used to calculate the different operating costs.

- Ops Cost
  - LG------X335, X320, X326, X301
  - OSV-----X500, X555, X526, X501
  - FHG-----X100, X120, X110, X135
  - SB------X400, X415, X425

X301=LG Mission Rate	X320=# LG Launch Sites
X326=Mass LG Fuel	X335=Launch Site Interval
X500=# OSV	X501=OSV Mission Rate
X526=Mass OSV Fuel	X555=OSV Crew
X400=# SBs	X415=SB Crew
X425=Mass of SB	X100=FHG Mission Rate
X110=FHG Payload	X120=# FHG Launch Sites
X135=FHG Launch Site Interval	

Figure 4.12 State Variables In Operating Costs

A brief description of the equations used to calculate the operating costs follows. For detailed cost equation derivation and the factors included in the cost calculations see Appendix E.

Launch site operating costs are based on the required launch rate from each site and the number of launchers (or launch sites). The FHG launch site operating cost includes an additional cost for ground based energy requirements.

LG, OSV, and SB operating costs include a cost for fuel. Fuel costs are derived from the amount of fuel required per mission and the frequency of missions. In addition, the SB and FHG have a cost for parts and expendables.

OSV and SB personnel costs are based on the number of crew members.

Initial Costs.

Initial costs are the costs incurred prior to the servicing system becoming operationally ready. Initial costs calculated are SSS Research and Development (R&D), purchase/fabrication, and deployment. Table 4.13 displays initial costs calculated for each subsystem.

Table 4.13

Initial Cost Matrix

SSS Subsystem	Initial Costs Modeled		
	R&D	Prod	Deploy
OSV vehicle	x	x	n
LG vehicle	x	x	n
FHG			
vehicle	x	x	n
launch site	x	x	n
SB vehicle	x	x	x

note: x indicates cost included
n indicates cost not applicable to subsystem

In most cost studies initial costs are amortized over the life of the system and then figured into the operating costs. This amortization is not done in this study because the life of any SSS cannot be predicted with any degree of certainty. However, a lump sum initial cost is still a good comparative measure of any SSS impact on the federal budget.

For this reason, decision makers interviewed felt the seperation of initial and operational costs was important and useful. Figure 4.13 displays the subsystem state variables used in the different calculations.

- Initial Costs
  - R&D
    - LG--- X325, X345
    - OSV-- X555, X545, X525
    - FHG-- X110, X360
    - SB--- X415, X425
  - Prod
    - LG--- X300, X325, X345
    - OSV-- X500, X545, X525, X555
    - FHG-- X120, X110, X360
    - SB--- X400, X425
  - Deploy
    - LG--- same all models
    - OSV-- same all models
    - FHG-- none
    - SB--- X400, X425

X300=# LGs	X325=Mass of LG
X345=LG Reliability	X360=Rendezvous Alt
X500=# OSV	X525=Mass of OSV
X545=OSV Reliability	X555=OSV Crew
X110=FHG Payload	X120=# FHG Launch Sites
X400=# of SBs	X415=SB Crew
X425=Mass of SB	

Figure 4.13 State Variables in Initial Costs

The R&D costs are based on subsystem structure mass, subsystem reliability, current state of technology, and R&D

team experience. The OSV and LG R&D costs increase as their reliability increases. In addition, the OSV cost decreases as the OSV manned intervention increases and robotic influence decreases (ie more robotic implies more R&D cost). Since life support equipment is on all manned space vehicles already there should be very little need for life support equipment R&D; however, considerable R&D will be required to produce a robotic OSV.

Production costs take into consideration subsystem structure mass and the number of units of each subsystem produced. The unit production costs include a cumulative learning curve adjustment. This adjustment accounts for decreasd cost per unit as the number of units produced increases. The OSV and LG costs are designed to increase as subsystem reliability increases. The OSV costs increase as the OSV manned intervention increases and robotic influence decreases. An assumption is made that as the OSV is designed to be more robotic, the R&D cost increases and production cost decreases. It is assumed that life support equipment requires high reliability and prcision to produce, while robotic equipment will be more

The SB is the only subsystem with a deployment cost. This cost is based on the SB mass to be delivered to orbit and the number of SBs.

Satellite Servicing System Reliability.

The SSS reliability is a measure of each SSS's ability to perform a specific mission. Here, the specific mission is defined as the system's ability to complete one servicing mission. In other words, the probability that the OSV is operational and can obtain needed supplies (from SB or LG) to service a satellite. Table 4.14 shows the subsystems included in the reliability measure calculation.

Table 4.14

Reliability Matrix

Model	Subsystems Included in Calculation			
	OSV	LG	FHG	SB
LG+OSV	x	x	n	n
FHG+LG+OSV	x	x	n	n
SB+FHG+LG+OSV	x	n	n	n

note: x indicates applicable to calculation
n indicates not applicable to calculation

Important simplifying assumptions are made in the FHG+LG+OSV and the SB+FHG+LG+OSV models. The FHG+LG+OSV model does not include the FHG reliability because an assumption was made that the LG is capable of carrying enough mass to resupply the OSV for one mission. Therefore, the FHG has no effect on the systems ability to perform the specific mission defined above. The SB+FHG+LG+OSV model has a built-in assumption that the SB would store a specified safety level of mass. Consequently, the reliability calculation assumes the OSV could continue to service satellites by using this

safety level mass (even if all launch systems were inoperable). This assumes the launch systems would be back in service before the SB safety level is depleted. A model constraint for the maximum time people can be in space before rotation (described later) must be relaxed for this assumption to hold. The SB is assumed to be 100 percent reliable (able to transfer mass to and refurbish the OSV 100 percent of the time).

The calculation of system reliability takes into consideration a subsystem's reliability and the number of units of each subsystem as depicted in Figure 4.14.

Reliability
- LG-- X300, X345
- OSV- X500, X545
- FHG- not in calculation
- SB-- assumed 100% reliable

X300=# LGs	X345=LG Reliability
X500=# OSV	X345=OSV Reliability

Figure 4.14 State Variables in Reliability

Mass Delivered to the Satellites.

As a measure of mission accomplishment this PI represents the total amount of mass delivered to the satellites per time (kg/hr). The mass consists of expendables and replacement parts for the satellites. This PI is calculated using the state variables "OSV missions per time" (X501) and "OSV payload per mission" (X510).

4.3.2.4 Physical Model Description. In this study the term physical model refers to the state and constraint (equality and inequality) equations within the model. The physical model is not some type of scale model or some type of hardware model. The purpose of the physical model is to identify and explain the important relationships that exist within a specific subsystem (intra-subsystem relations) and the relations that exist between the different subsystems (inter-subsystem relations) for each potential SSS. Figure 4.15 is a schematic of these relations. It is designed as an aid to understand the discussion in the following sections (4.3.2.4.1 and 4.3.2.4.2). The first column in Figure 4.15 is a complete listing of all the state variables (see Table 4.9 or Appendix F). The state variables are grouped according to whether they describe a specific subsystem's characteristics (physical descriptions) or describe how the subsystem is used (subsystem usage).

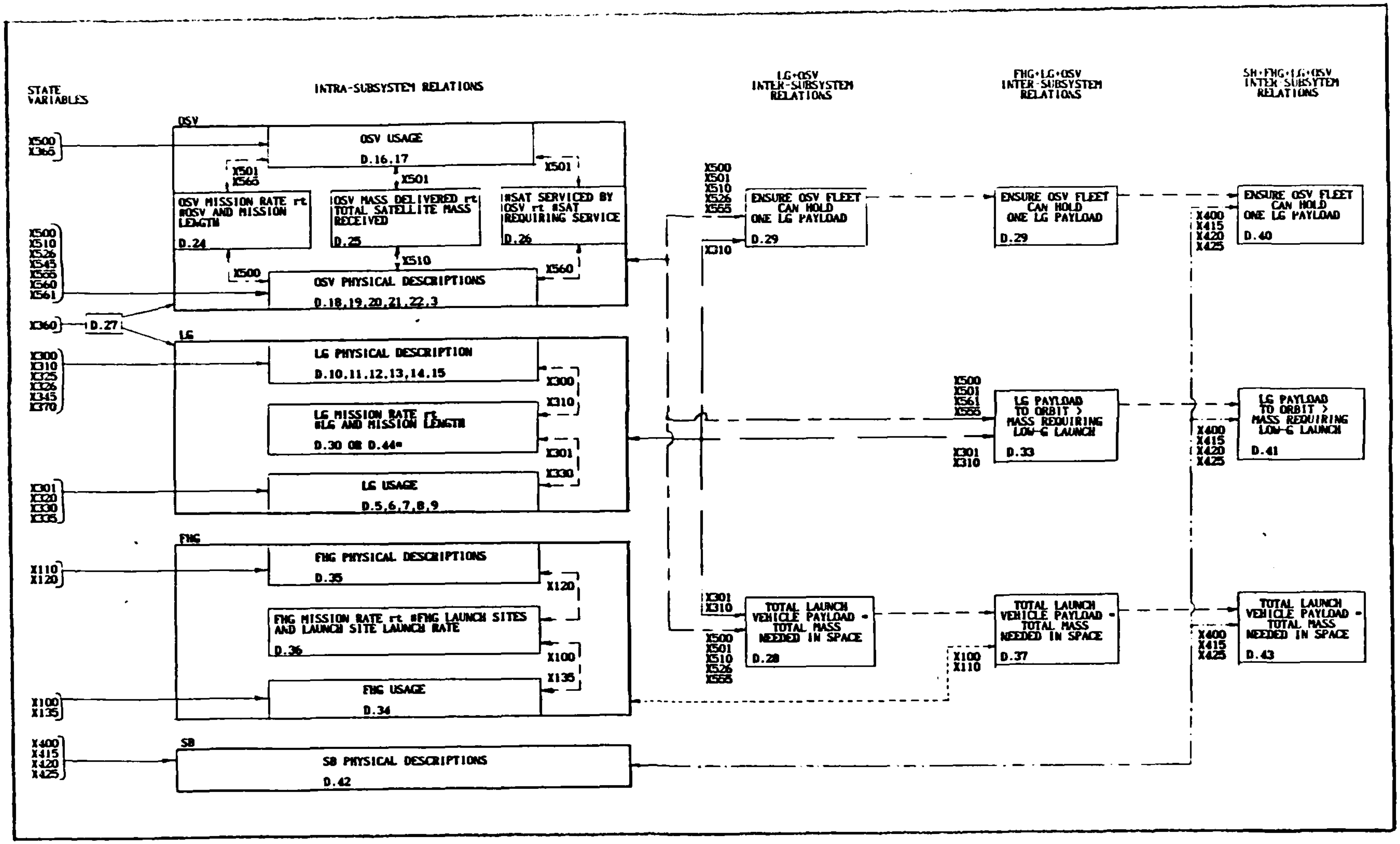


Figure 4.15 Physical Model Schematic

The second column has four large blocks representing the four subsystems used in some or all of the potential SSS. The smaller blocks inside each larger subsystem block represent an equation or group of equations relating the different subsystem state variables to each other. The titles of the smaller blocks represent the type(s) of equations grouped in the box. The "D.nn" represents the equations located in Appendix D associated with the box title. The arrows represent the existance of shared state variables between any two boxes. The state variable symbols printed beside each arrow represent which variables are shared. For clarity the exogenous variables are not shown in this schematic because these "variables" are in fact constants. Figure 4.15 is designed to graphically show how the states of each subsystem interact and influence the states of the other subsystems. It is these states that will be varied to generate optimal SSS realizations.

The third, fourth, and fifth columns represent the inter-subsystem relations that exist for each of t' poten- tial SSS. The LG+OSV system, which is in column three, is the simplest and most basic SSS. Therefore, the addition of the FHG and SB subsystems, which are shown in column four and five respectively, result in modifications to the basic SSS. In addition to the above defined use of arrows, those arrows going from a column three box to a column four or five box represent the same basic equation with modifica-

tions to account for the additional subsystems. Again the D.nn represent the equation numbers from Appendix D. The next two sections present qualitative descriptions of the equations represented in each of the boxes.

4.3.2.4.1 <u>Intra-Subsystem Relationships</u>. Prior to the discussion of each of the individual subsystem internal relationships, a few assumptions and general relationships common to all the subsystems will be discussed.

General Assumptions and Relations

1. All subsystems must be able to hold adequate fuel, life support, and parts to function from one resupply time until the next. For example, the OSV must carry enough fuel to provide the thrust to complete a servicing mission (Eqs (D.15), (D.17), and (D.22)).

2. The OSV, LG, and FHG have limitations on their vehicle structure mass ratios to prevent carrying more mass than the structure can support (Eqs (D.10), (D.11), (D.18), and (D.19)). The FHG has an assumed structure mass ratio of 0.1 which is embedded in intermediate variable equationI113 (Appendix F, I113). The SB has the mass stored to structure mass ratio set equal to a constant (Eq (D.42)).

3. Relations exist between a subsystem mission rate, the number of launch sites, and the number of units of each subsystem. These relations require estimates of mis-

sion lengths, vehicle refurbishment time between missions, and launch site refurbishment time between launches from the same site (Eqs (D.6), (D.7), (D.8), (D.9), (D.17), (D.24), (D.30), (D.34), (D.36), (D.44)).

4. All mass used by satellites and service vehicles must be launched from Earth. There is no consideration given for moon or asteroid originated mass.

5. Service vehicle mission lengths and the time between LG launches must have an upper bound to accomodate the maximum time people can be in space before returning to Earth. Exposure to radiation, psychological health, and quality of job performance are reasons for limiting the time people stay in space. This assumption requires an LG be launched as least as often as the maximum time people can remain in space (Eqs (D.5), (D.16)).

6. Service vehicles and launch vehicles must be able to rendezvous and transfer mass (people,parts,fuels). The different rendezvous altitudes and time required to transfer mass from one vehicle to another, or from a service vehicle to a satellite, affect the amount of fuel the vehicle must carry and the vehicle mission length.

7. By definition the reliability of any subsystem lies between zero and one. Therefore, the OSV and LG subsystems reliability must be upper and lower bounded (Eqs (D.13), (D.14), (D.20), (D.21)).

8. The time an orbital vehicle can remain in a stable orbit above the Earth is dependent on its altitude. Therefore, the minimum orbit altitude "Minimum orbit Altitude" (U58) for the SB and the rendezvous orbit altitude for other vehicles (OSV,FHG,LG) must be input to the model (Eq (D.27)). For the LG+OSV SSS model the minimal orbital altitude was set at 185km. This minimum altitude allows for a vehicle's orbit to remain stable (ie. not experience significant orbital degradation from atmospheric effects) for 3 days (Bate, 1971: 152; Dept. of AF, 1985:3-13). For the other two SSS models the exogenous input should be set to a larger value depending on the required length of time a vehicle is expected to remain in orbit. Table 4.15 provides a list of altitudes and the length of time an orbit is expected to remain stable.

Table 4.15

Spacecraft Altitude vs
Time in Orbit (Dept. of AF, 1985:3-13)

Nautical miles	Kilometers	Days
85	157.4	0.5
100	185.2	3
150	277.8	35
200	370.4	200
300	555.6	4000

OSV Subsystem.

The OSV is required to make orbit position and altitude transfers. A multitude of orbital transfer methods exist; however, our model will use Hohmann orbit transfers which minimize delta velocity requirements which in turn minimize fuel mass requirements (Eq (D.22)). The OSV is assumed to be propelled by a chemical system with fuel specific impulse fixed at an expected technological upper limit of 500 sec "OSV ISP" (U24). The delta velocity equations and fuel consumption equations are explained in Appendix G.

Equations D.23, D.25, and D.26 relate the OSV payload and number of satellites serviced per mission by the OSV to the amount of mass the satellites receive and the number of satellites needing servicing.

LG Subsystem.

The LG launch system has one or more stages (Eq (D.12)) and a set value of 400 sec for fuel specific impulse (Isp) "MLG ISP" (U33). The equations for LG required delta velocity to orbit are derived using approximate values for drag, gravity, Earth's rotation, and trajectory shaping losses from (Dept of AF, 1965:246) Eq (D.15). Although the LG is not identified as a manned or unmanned vehicle, it must be capable of carrying men if the SB or OSV are manned subsystems. The LG will go into the rendezvous orbit, rendezvous with enough OSVs or a single SB, unload its payload, and return to Earth (Eqs (D.30) and (D.44)).

FHG Subsystem.

The high-G launch vehicle is assumed to receive an initial delta velocity from an Earth based energy source. The launch velocity is equivalent to the velocity an orbital vehicle would have if it was at the perogee of an elliptical orbit. The appogee of the launch trajectory is at the rendezvous altitude. When the high-G vehicle leaves the Earth's surface no additional thrust is assumed to be required except for an orbital circularization thrust at appogee. This thrust is required to prevent the FHG vehicle from re-entering the atmosphere and being destroyed prior to the payload being off-loaded. The Earth based energy requirement is calculated as a change in kinetic energy the FHG vehicle experiences. Concerns for air drag and inclination changes have not been modeled; however, the total amount of energy needed is assumed to be twice the energy required from the change in kinetic energy calculation. Intermediate variable equations calculate the above relations and are inputs for the FHG cost equations (see Appendix F, I100 to I120). Eq (D.35) prevents the optimization computer program PROCES from trying to reduce the FHG payload to ridiculously small amounts, but launched very often.

SB Subsystem.

The SB is modeled as a warehouse and OSV refurbishment facility. The ratio of SB structural mass to SB mass storage capacity is set equal to a constant value of 1.0 "SB structure mass to storage mass ratio" (U133) Eq (D.42). The SB is assumed to store all types of mass that is required in space with a predetermined safety level "SB safty level" (U130) of one month. All payload aboard the LG launch system must be off-loaded to the SB (D.40). Payload aboard the FHG may be off-loaded directly to the servicing vehicles or to the SB. Since the FHG is assumed to be expendable, the FHG vehicle could act as a temporary on-orbit storage facility. Thus if the LG transports fuel, it must off-load the fuel to the SB where it will be stored. If the FHG carries fuel, the SB need not store it. No attempt is made to model the time and fuel requirements for the OSV or LG to rendezvous with the FHG and off-load the FHG payload or tow the FHG to the SB. In the models without an SB, the FHG just has to get into orbit because an assumption is made that the OSV and LG could rendezvous at the FHG vehicle location in orbit. The OSV and LG must go to the SB each mission; however, the FHG is not required to rendezvous with the SB. Therefore, possible alternatives include the FHG circularization thrust placing the FHG in a position to rendezvous with the SB or the OSV rendezvous with the FHG just before or just after rendezvousing with the SB.

4.3.2.4.2 Inter-Subsystem Relationships. The inter-subsystem relationships describe the relationships between the different subsystems. These relationship equations are presented as boxes in columns three through five in Figure 4.15. Column three is for the LG+OSV SSS, column four for the FHG+LG+OSV, and column five for the SB+FHG+LG+OSV SSS. Therefore, the simplest LG+OSV inter-subsystem equations are presented first followed by the more complex FHG+LG+OSV and SB+FHG+LG+OSV interrelations.

LG+OSV Inter-Subsystem Relations.

Since the LG is the only launch system, the total mass required in space (satellite and OSV needs) must be carried into orbit by the LG fleet (Eq (D.28)).

The OSV fleet must be able to hold a complete LG payload to avoid the LG acting as a storage facility and remaining in orbit for long periods of time. Simply put, when the LG goes into orbit enough OSVs must be at the rendezvous location to hold the entire LG payload so the LG can immediately return back to earth to begin another mission (Eq (D.29)).

FHG+LG+OSV Inter-Subsystem Relations.

The addition of the FHG to the LG+OSV model (Fgure 4.15, FHG+LG+OSV Column four) requires the revision of one inter-subsystem equation, the creation of a new inter-subsystem equation, and the addition of FHG cost equations.

The previous requirement that the LG carry all mass to orbit is replaced with the total mass carried by the LG and FHG equal to the total mass required in space (ie. mass required by spacebased subsystems (OSV) and the mass delivered to the satellites (Eq (D.37))).

Since the FHG is capable of only launching mass that can withstand a high-G launch, the mass needed in space (fuels, parts, life support, and people) must be split into two groups: mass that can withstand a high-G launch (fuels and some parts) and mass that must be low-G launched (people, life support, parts). An assumption is made that all life support mass would be low-G launched. Eq (D.33) represents the requirement that the total payload mass launched by low-G launch systems must be greater than or equal to the mass requiring low-G launch.

SB+FHG+LG+OSV Inter-Subsystem Relations.

The addition of the SB to the FHG+LG+OSV model causes three inter-subsystem equations to change, one LG intra-subsystem equation change, the addition of the SB cost equations, and a change to the reliability PI equation.

The requirement for the OSV fleet to hold a single LG payload is replaced with a requirement for a single SB to hold an entire LG payload (Eq (D.40)). The relation between the total mass the LG and FHG must carry to space is increased to include the SB required mass (Eq (D.43)). The

minimum amount of mass the LG must carry is increased to include the SB low-G launched mass requirements (Eq (D.41)). Since the LG is now transfering mass to the SB instead of to an OSV, a LG to SB mass transfer rate is used instead of an G to OSV transfer rate (Eq (D.44)).

4.4 Chapter Summary

This chapter has presented the model development from the initial conceptualization phase through the development of analytical models. The three models have identified important relationships existing between the different subsystems and a set of criteria for comparing potential servicing systems. The models should be an excellent starting point for future more detailed SSS models. Future models should examine the accuracy of the assumptions made in this study and provide more detailed analysis where necessary. The next chapter will provide an analysis and optimization of the LG+OSV model. Availability of resources (computer and manpower) precluded the analysis of the other two models.

V. System Analysis

5.1 Introduction

This chapter describes and demonstrates the analysis step of the systems engineering (SE) methodology as introduced in chapter II. The purpose of this step is twofold: (1) to generate a solution set based on engineering requirements, and (2) to describe how good, in an engineering sense, that solution is. These two tasks will be referred to as "non-dominated solution set (NDSS) generation, and solution validation." Figure 5.1 depicts the information flow between the two tasks of the analysis step as it relates to the other parts of the SE methodology.

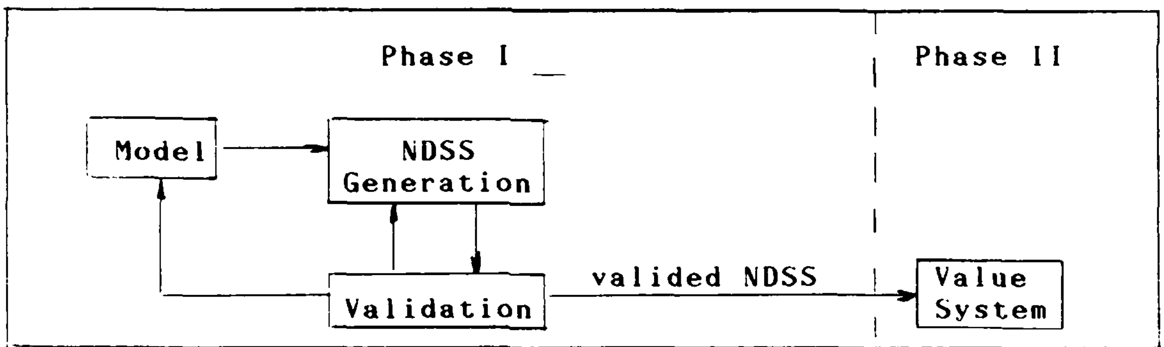


Figure 5.1 Analysis Step Information Flow

The model, as developed in chapter IV, is the medium for generating the NDSS. The results of the validation task allow the analyst to determine if more iterations through the SE process may be necessary. Usually, this means either refining the model or changing the NDSS generating technique, after which an NDSS is again generated and checked

for validity. This process is continued until the NDSS is validated. The final NDSS generated must be of sufficient detail to allow implementation. As described in Chapter II, this marks the conclusion of Phase I of the SE approach. The valided NDSS is then the input to the value system application (decision making) process of Phase II.

The method of generating the NDSS depends on the type, form and detail of the model. In the initial stages of the project the models may be as simple as the word equations presented in section 4.2. The NDSS could be generated by a technique using pairwise comparison of the performance indicies (PI's). As the model becomes more complex (like the analytical models in chapter IV) different techniques, such as vector optimization, are applied. Except for simple problems, vector optimization solution generation techniques must be mechanized on a digital computer. The computer program PROCES (DeWispelare and Clark,1983) was used to generate the NDSS for this study.

Validation is the process of ensuring that the abstract representation (model) of the physical system behaves like the real system. The degree to which the model behavior matches the real system depends on the structure and detail of the model. Since the model is only an abstraction, the results obtained from it are only useful to within certain limits. These limits depend on the areas of real system behavior that are of interest and the assumptions that are

used during construction of the model. The focus of the validation task also varies as the project develops. Initially, the only concern may be realizability of the solutions. In the more advanced stages of a project other factors, such as the sensitivity of the results to model parameter changes, become more important.

The remainder of this chapter will present the analysis results for the model of a low-G launch vehicle and Orbital Servicing Vehicle system (LG+OSV). The other system models described in Chapter IV can be analyzed using the same techniques; however, resource constraints prevented their inclusion in this effort. The validity of the model and NDSS is addressed (in section 5.3) in terms of realizability, optimality and sensitivity. A presentation of the concepts necessary to understand the analysis results is given prior to the discussion of the results.

5.2 Concepts

The following presentation of concepts (terms, theory, tools, and techniques), used for the LG+OSV model analysis is presented in two parts. The first part describes important concepts used for the NDSS generation task, while the second part discusses the concepts used for the validation task.

5.2.1 Concepts for NDSS Generation. As noted in Chapter IV, the four objective functions (PI's) of the SSS state

space model are conflicting; specifically, minimize initial and operating costs while maximizing mass delivered to orbit and reliability. A traditional approach to solving such a problem is to optimize the system with respect to one objective, while fixing the remaining objectives at acceptable levels. Typically, this approach will require further suboptimization and rarely provides a decision maker enough information to make the best possible choice in as short a time as possible. A desirable alternative to the traditional approach is vector optimization. Vector optimization generates a set of solutions (called an NDSS) and a means for analyzing the tradeoffs between the performance indices.

The following paragraphs describe the vector optimization concepts. The results of vector optimization have distinct meaning when both the model and PI equations of the statespace model are convex. However, for this study, these equations (functions) are not convex. Therefore, a discussion of what impact convexity has on determining the NDSS will be presented. Then a discussion of how to solve a vector optimization problem (VOP) by casting it into the form of an iterative scalar optimization problem. The scalar optimization methods chosen for use in solving the VOP are then described. The section concludes with a discussion of how the concepts presented are implemented for the nonconvex model of this study.

5.2.1.1 Vector Optimization (DeWispelare, 1984: Ch II). The goal of vector optimization is to generate optimal solutions (realizations). Each solution has the components of the vector of PI's, or objective functions, extremized. All the solutions from each of the potential satellite servicing systems are combined into a set of solutions. A common formulation used to implement various optimization processes for a vector of PI's is given by:

$$\begin{aligned} &\text{MAX } \underline{Z}(X) = \text{MAX}[Z_1(X), Z_2(X), \ldots\ldots, Z_p(X)] \\ &\text{Subject to:} \\ &\quad G_j(X) >= 0 \; ; \; j = 1,2,\ldots,m \\ &\quad X_k >= 0 \; ; \; k = 1,2,\ldots,n \end{aligned} \tag{5.1}$$

where $\underline{Z}(X)$ is a p dimensional vector of PI's, X is an n-dimensional vector of state variables. The G_j's are the constraints which define the feasible region of the X (state) space. The concept of Pareto optimality or non-dominance is used to identify the efficient set of realizations characterized by the state variable values.

A specific solution is a non-dominated solution (or Pareto optimal solution) if its vector of PI's is not dominated by another realization's vector of PI's. For solution A to dominate solution B (for a maximization case) at least one PI of solution A must be strictly greater than the same PI of solution B while the remaining objectives in solution A are greater than or equal to the corresponding objectives in solution B. Consider the following example:

$$\underline{Z}^{a} = \{1.2.3\} \qquad \underline{Z}^{b} = \{1.1.3\} \qquad (5.2)$$

where $\underline{Z}^a$ and $\underline{Z}^b$ are the vectors of PI's for solutions A and B respectively. Since the second component of $\underline{Z}^a$ is greater than the corresponding component in $\underline{Z}^b$ and the remaining components are equal. the vector $\underline{Z}^a$ dominates the vector $\underline{Z}^b$; or equivalently. solution A dominates solution B.

The process of generating a NDSS includes the optimization of the vector of PI's combined with a check for dominance to identify the members of the NDSS. In practice. when the objectives are conflicting no single solution completely dominates all the others. The NDSS can be thought of as forming an "efficient frontier" in the p dimensional PI space (defined by $Z_1, Z_2 \ldots Z_p$). This frontier represents the best that the system being optimized can do with respect to the vector of p performance indicies. Put a different way. for solutions on this frontier. no PI can be improved without degrading another PI.

As an illustrative example of non-dominance consider the following two dimension case (p=2) of three solution vectors out of a set of N vectors (found by using an optimization algorithm):

$$Z^1(X) = [\ Z_1^1(X^1) = 2,\ Z_2^1(X^1) = 2\ ] \qquad (5.3)$$

$$Z^2(X) = [\ Z_1^2(X^2) = 2,\ Z_2^2(X^2) = 3\ ] \qquad (5.4)$$

$$Z^3(X) = [\ Z_1^3(X^3) = 3,\ Z_2^3(X^3) = 2\ ] \qquad (5.5)$$

Pictorially, $Z^2(X)$ and $Z^3(X)$ can be thought of as points on the "efficient frontier" as illustrated in Figure 5.2.

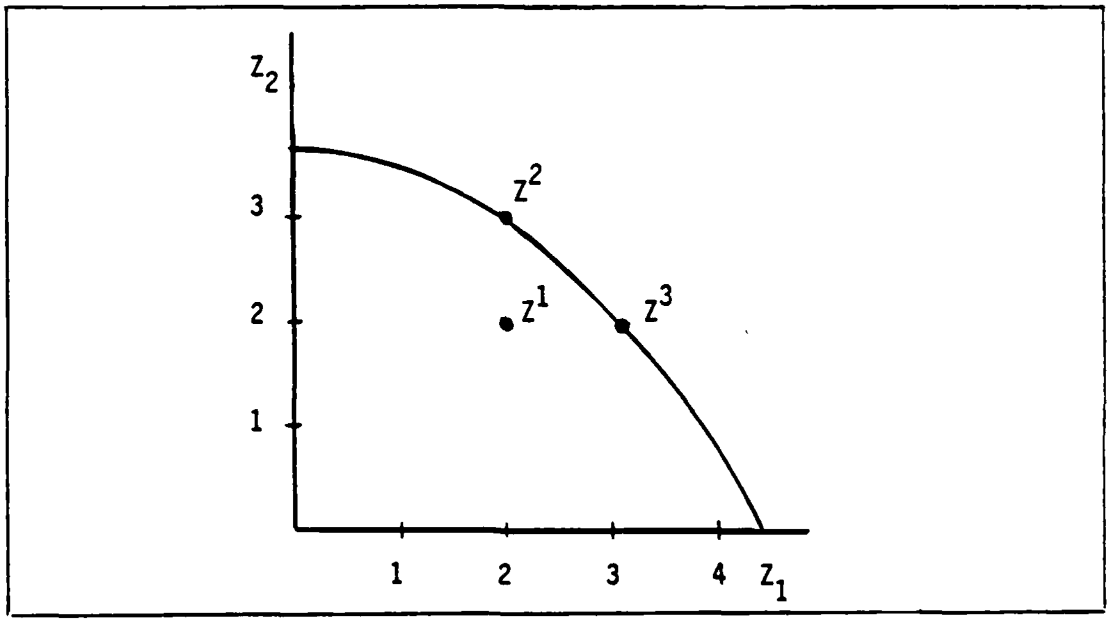


Figure 5.2 Efficient Frontier

As can be seen $Z^2(X)$ dominates $Z^1(X)$, therefore $Z^1(X)$ is not a member of the NDSS. Neither $Z^2(X)$ or $Z^3(X)$ dominates the other. If none of the remaining N-3 vectors dominate $Z^2(X)$ and $Z^3(X)$, then $Z^2(X)$ and $Z^3(X)$ are members of the NDSS.

There are several techniques available for finding solutions to the VOP represented by Eq (5.1). In this study, the weighted norm approach and the method of proper

equality constraints as described by (Chankong and Haimes, 1983: Ch 4) are used. These will be referred to as the weighting and constraint techniques respectively. Both methods transform the $\underline{Z}(X)$ vector of PI's into a psuedo-scalar optimization form to which standard scalar optimization methods can be applied.

The weighting technique is formulated as follows:

$$MAX\ J = MAX \sum_{r=1}^{p} W_r * Z_r(X)$$

$$\begin{aligned} &\text{Subject to:} && && (5.6)\\ &G_j(X) \geq 0: && j = 1,2,\ldots\ldots,m\\ &H_l(X) = 0: && l = 1,2,\ldots\ldots,q\\ &X_k \geq 0: && k = 1,2,\ldots\ldots,n \end{aligned}$$

where W_r is a scalar weighting coefficient for the r PI's. The procedure is to repeatedly perform a scalar optimization on J for different values of the W_r's. The allowable ranges over which the parameters W_r are varied can be estimated from rough calculations, expert opinion, or scalar optimization for each $Z_r(X)$. Each optimal J has an associated $\underline{Z}(X)$ vector of objective values. After each iteration this vector of PI's is checked for membership in the NDSS. If the problem is convex, then each solution corresponding to a set of weights will be a member of the NDSS. Furthermore, if all combinations of W_r's are chosen to meet Eq (5.7), then this technique will completely describe the NDSS.

$$\sum_{r=1}^{p} W_r = 1 \tag{5.7}$$

This technique describes the NDSS well. but is computationally burdensome. The constraint technique is simpler to solve numerically.

The constraint technique is formulated as follows :

$$\begin{array}{lll} \text{MAX } Z_a(X) & & \\ \text{Subject To:} & & \\ \quad G_i(x) \geq 0 & i = 1,2,\ldots,m & \\ \quad H_l(X) = 0: & l = 1,2,\ldots,q & \\ \quad Z_r = C_r & r = 2,3,\ldots,p & r \neq a \\ \quad X_j \geq 0 & j = 1,2,\ldots,n & \end{array} \tag{5.8}$$

One PI is chosen to be extremized while the others are augmented to the problem as additional proper equality constraint equations. This scalar optimization problem is then solved iteratively for different values of the C_r's. The C_r's are scalar values picked to correspond to the expected range of the respective PI. The optimum solution of each iteration with a specific set of C_r's is only a potential member of the NDSS. The potential member must be compared against previously identified solutions for dominance and inclusion in the NDSS.

Whether using the weighting or constraint technique, three basic processes need to be performed iteratively:

1. Select a new set of fixed weights (W_r's) or constraints (C_r's).

2. Perform optimization of the scalar objective function.

3. Update the NDSS by determining non-dominance of the new solution with respect to the solutions in the current NDSS.

The choice of which technique to use depends on many factors, the most important of which is the convexity of the problem. If the problem is convex, the above three processes can be performed efficiently. However, if the problem is non-convex, more effort is required. To understand what is meant by these statements, some explanation of convexity is needed.

5.2.1.2 Convexity. Convexity considerations play a critical part in the analysis. The concepts presented here will not be mathmatically rigorous but will instead try to show the impact of convexity on the vector optimization problem. Definitions of terms (such as convex set and convex function) and appropriate theorems can be found in (Fiacco and McCormick, 1968: Ch 6), or similar texts on nonlinear optimization. Three important basic concepts from convex set theory are:

1. The intersection of two convex sets is a convex set.

2. The mapping of a convex set of points by a convex function is a convex set.

3. The sum of convex functions is a convex function.

Figure 5.3 illustrates the first concept. Each circle represents a convex set; therefore, the intersection of the two sets, S_x, is also a convex set.

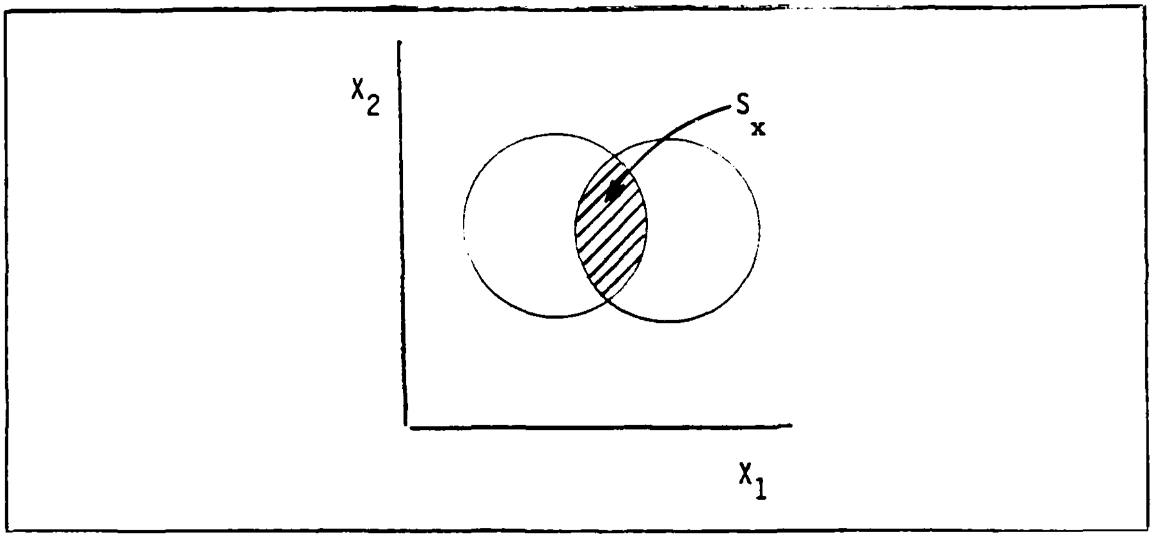


Figure 5.3 Convex Sets

Figure 5.4 illustrates the second concept. In the figure, Z_1 and Z_2 are convex functions that map the convex set of points S_x in X-space, into a set of points S_z in Z-space. Thus S_z is a convex set of points. While this example was for a two dimensional X space and Z space, the concept can be extended to higher dimensional spaces. The generalization is that if set S (a subset of Euclidean n space) is convex and if Z_p p=1...r are convex functions, then the resulting set S_z (a subset of Euclidean p space) will be convex.

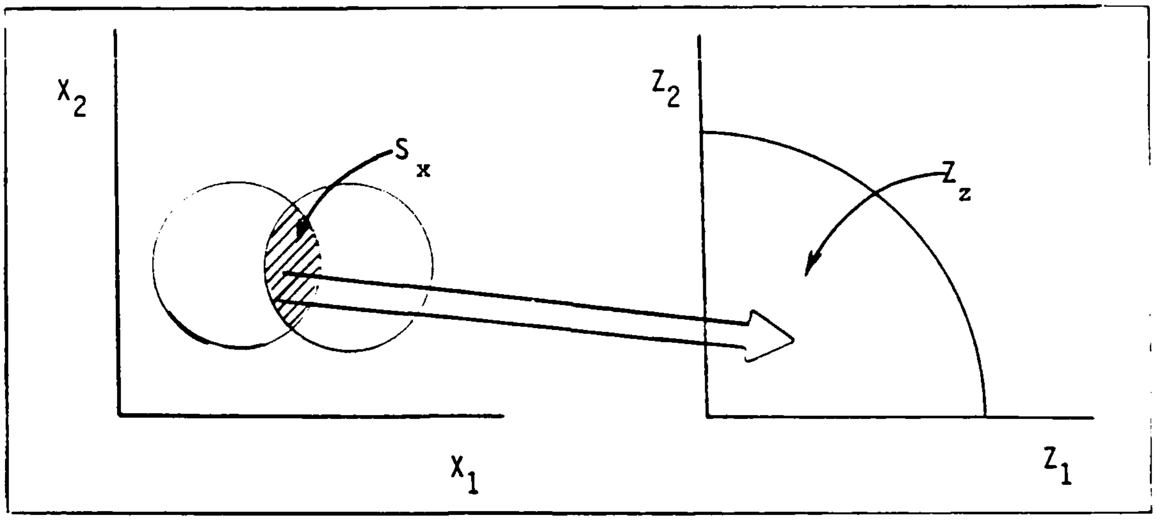


Figure 5.4 Convex Mapping

The third concept means that the linear combination of convex functions is also a convex function. These three concepts can be directly applied to the vector optimization problem.

To understand the implications convexity has on the VOP, the structure of the model must be understood. The model is composed of two sets of equations: (1) the performance indicies and (2) the constraints. The constraints define the feasible region (in X-space) from which the solutions to the VOP must come. If the constraint equations define a convex set (region), then by convexity concept (2) the feasible region is also convex. The PI equations map the set of points in the feasible region into the objective vector space. For instance, in Figure 5.4 the set of points S_x (defined by the constraints in the n-dimensional state space) are mapped into a set of points S_z (in the p-

dimensional objective space) by the PI equations Z_1 and Z_2 If S_x is convex and the PI equations are convex, then the region S_z defined by this mapping is a convex set by convexity concepts (1) and (2). Now the weighted and constraint vector optimization techniques described above can be examined in more detail for use on convex and non-convex problems.

The weighted technique linearly combines the PI's (Z space mapping functions) into a single scalar function. Thus by convexity concept (3) this function of PI's is convex if the PI equations are convex. The constraint technique optimizes one PI and adds the other PI's as extra equality constraints. The convex problem, whether solved by either technique, has the property that any local optimum for a vector optimization sub-problem is the global solution to that sub-problem. The sub-problem is defined as the problem associated with a particular iteration of the W_r's or the C_r's as described in Eqs (5.6) and (5.8). For a convex sub-problem the weighted technique will always produce a member of the NDSS (Chankong and Haimes, 1968: Ch 6). The solution to the convex sub-problem found by the constraint technique however, may not always find a point on the efficient frontier (NDSS). This makes it necessary to compare solutions found by this technique to other members of the NDSS for non-dominance.

If either the constraint equations or the PI equations is non-convex, then identifying the members of the NDSS using either technique becomes more difficult. Figure 5.5 illustrates this situation.

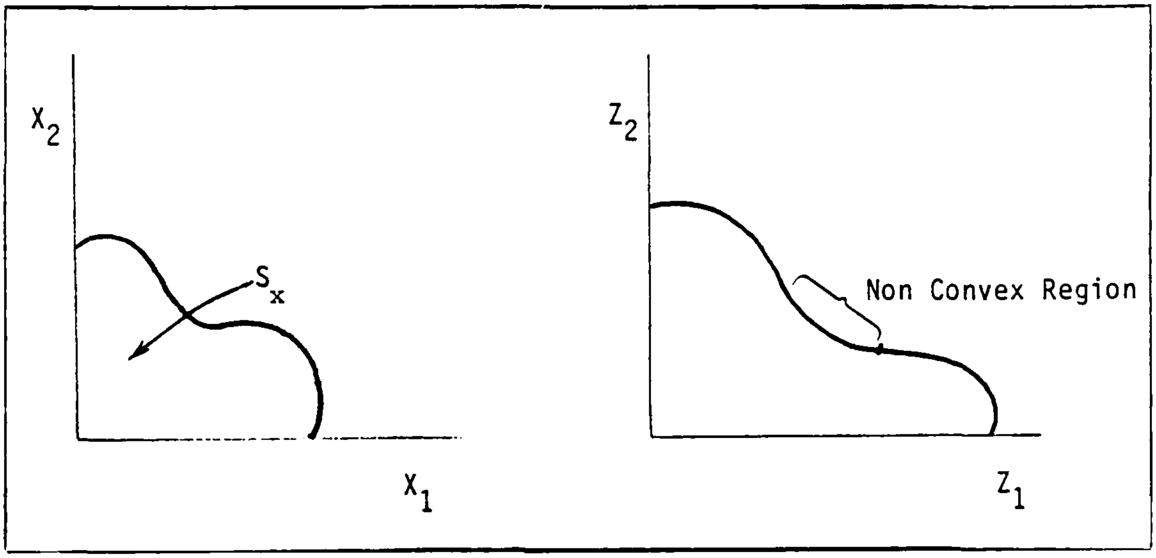


Figure 5.5 Non-Convex Mapping of Constraint Space to Objective Space

As can be seen from Figure 5.5, there can exist regions of non-convexity in the objective space. These non-convex regions cannot be found by use of the weighted technique decribed by Eq (5.6). To illustrate this, Figure 5.6 shows how the weighted sum (J) of the PI's describes a line which is tangent to the efficient frontier.

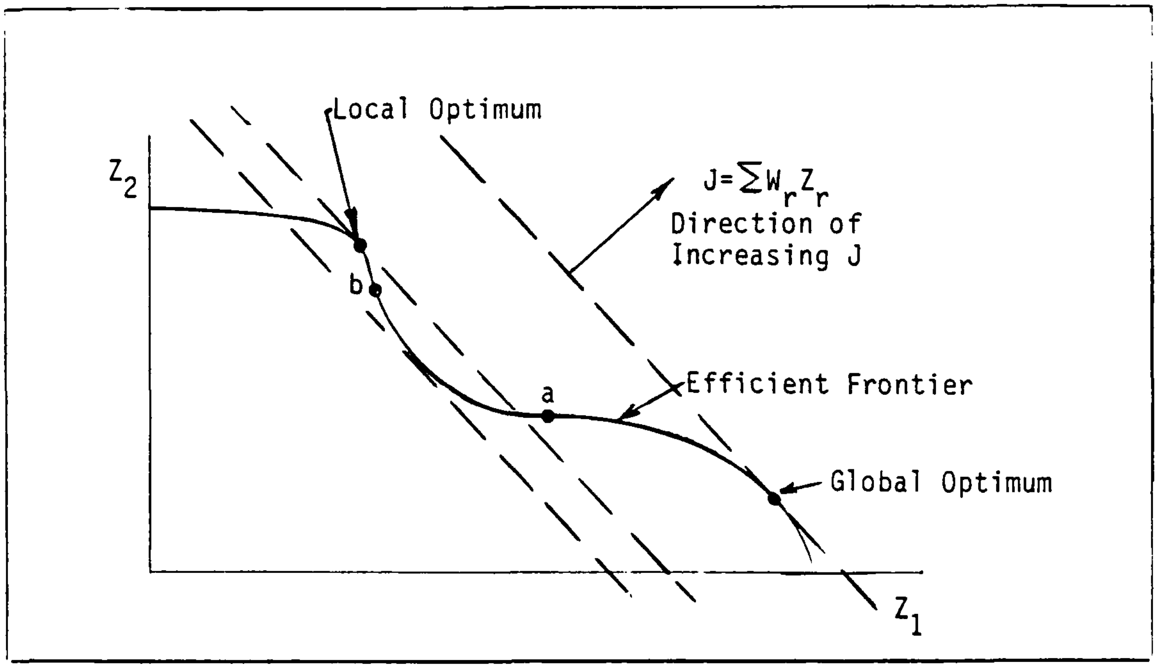


Figure 5.6 Weighted Efficient Frontier Generation

The point of intersection is the non-dominated solution for a fixed set of weights. As the weight parameters W_r change, so does the slope of the line. As the value of the weighted sum (J) of the PI's changes, it will define local and global maximums as shown. The points on the efficient frontier that lie between a and b cannot be located by any set of weights; this graphically demonstrates why all the members of the NDSS cannot be found by this method under non-convex conditions. As the value of J increases (under maximization), any point of intersection of the tangent line between points a and b will still allow the algorithim to increase the value of J along the efficient frontier without violating any constraints.

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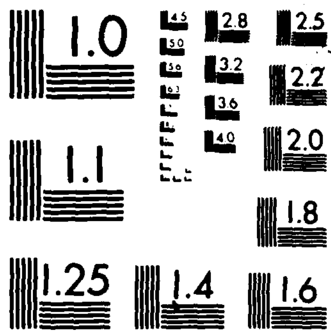

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The constraint technique, Eq (5.8), performs its function by fixing p-1 of the PI's and maximizing the remaining unfixed PI. Figure 5.7 illustrates this situation for a two dimensional PI problem, where Z_1 is set equal to C_r.

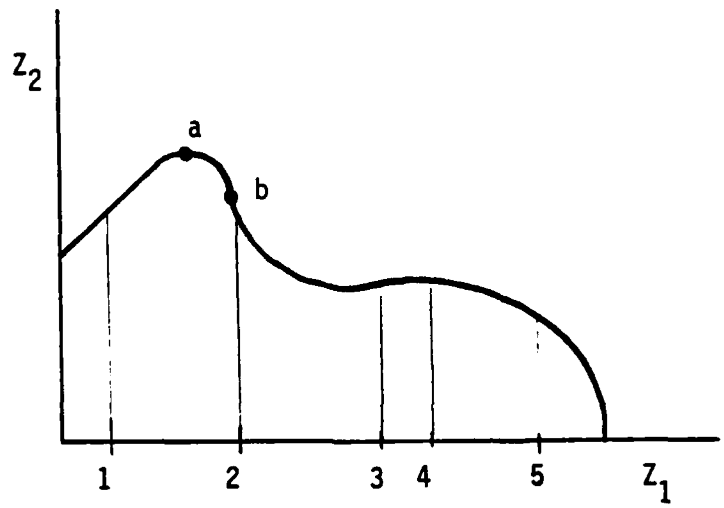

Figure 5.7 Constrained Optimization

The sub-problem is solved for each value of the C_r's where $r=1,...,5$. The solution (Z_2) for the grid point number 1 is clearly dominated by any NDSS member between points a and b and is thus not a member of the NDSS. Note that unlike the weighted technique this technique can find every point on the efficient frontier.

The strengths and weaknesses of the two VOP techniques in generating an NDSS for a non-convex problem have been shown. Section 5.2.1.4 will discuss an implementation of the two techniques which takes advantage of each one's strengths and efficiently generates a complete and fully described

NDSS.

5.2.1.3 Scalar Optimization Methods. Once the VOP problem has been cast into either the weighted or constraint technique forms, the constrained sub-problems must be optimized using scalar optimization techniques. This can be done by converting the constrained optimization problem to an unconstrained optimization problem (Fiacco, and McCormick, 1968: Ch4). This conversion requires the creation of a penalty for the weighting technique (Eq (5.9)) and the constraint technique (Eq (5.10)) (Mylander, 1971: 1).

$$\text{Max } P(X,r) = \sum_{i=1}^{p} W_i \, Z_i(X) + r \sum_{i=1}^{m} \ln[G_i(X)] + \sum_{i=1}^{q} [H_i(X)]^2 / r \quad (5.9)$$

$$\text{Min } P(X,r) = Z_a(X) + r \sum_{i=1}^{m} \ln[G_i(X)] + \sum_{i=1, i \neq a}^{p} [Z_i(X)]^2 / r + \sum_{i=1}^{q} [H_1(X)]^2 / r \quad (5.10)$$

where $H_i(X)$ are the equality constraints, $G_i(X)$ are the inequality constraints and $Z_i(X)$ are the performance index equations. The problem is then solved as an unconstrained optimization problem over the feasible region of the state space (defined by the $G_i(X)$). This is done by picking an arbitrary positive value for r. The unconstrained problem is then solved. The resulting solution state vector X (associated with the extreme P value) is then used as a starting point to search for a new solution associated with

a smaller value of r. This process is repeated until the change in the value of successive penalty function optimal solutions are within a desired range (domain of attraction). The final solution is considered to be the optimal solution for the original constrained problem.

5.2.1.4 Implementation. When the objective function or the constraints are non-convex, most minimization techniques cannot guarantee that a global solution has been found. Usually, given an initial feasible X vector starting value, the procedure will only converge to a local minimum. Thus to define the efficient frontier of the model the problem must be iteratively solved with many initial starting points for every value of either the W_r or the C_r.

The following procedure is recommended for non-convex problems (Chankong and Haimes, 1983: Ch 6):

1. generate an NDSS with the weighting technique, using Wr between 0 and 1 with all combinations of extreeme values that satisfy $\sum W_r = 1$
2. perform the constraint technique with initial state vector starting values, including the NDSS from step 1, and vary the C_r's over the range of the PI values found in step 1.

Step 1 generates a range of values for the PI's, and gives a rough picture of the effecient frontier. The constraint technique can then be used to trace out the remainder of the efficient frontier.

The computer program PROCES (Clark and DeWispelare,

1985) is designed to accomplish the task of vector optimization. This Fortran program was implemented on a CDC Cyber 175. The basic flow of the PROCES algorithm is shown in Figure 5.8.

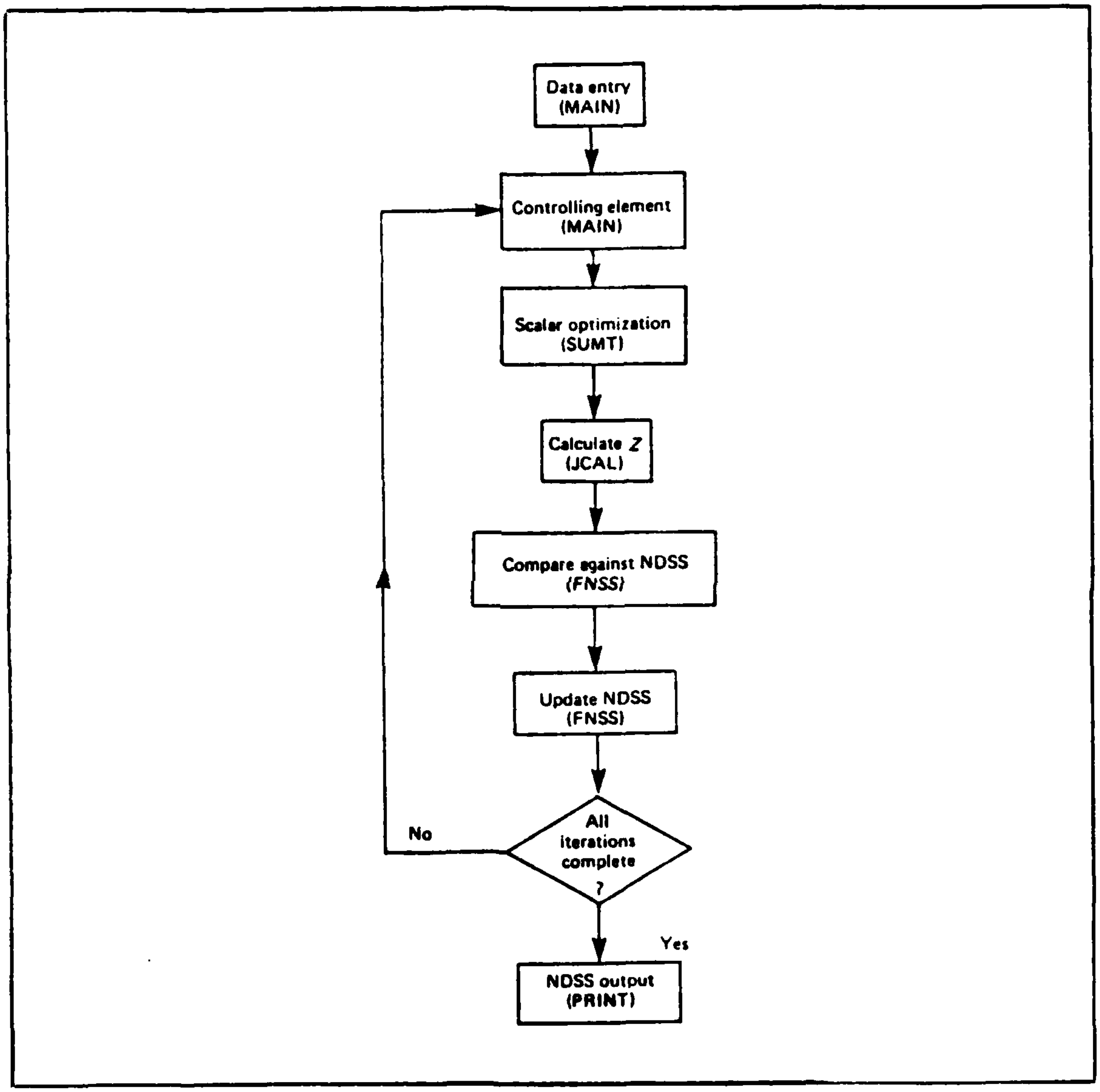

Figure 5.8 Program PROCES Flow Diagram
(Clark and DeWispelare, 1985)

Subroutine MAIN is the primary controlling element of the program. It mechanizes the application of the con-

straint or weighted technique by iterating the values of either the C_r's or the W_r's in Eq (5.8) and (5.6). Scalar optimization is performed by the sequential unconstrained minimization technique SUMT (Mylander,et al, 1971). The solutions from the SUMT subroutine are rescaled in subroutine JCAL. This step is a result of having scaled the objectives in the model to maximize the computational efficiency of the algorithm SUMT. In the subroutine FNSS the rescaled solutions are then compared with other members of the NDSS, dominated solutions are eliminated, and a new NDSS is generated. Finally the NDSS is displayed by the PRINT subroutine. The PROCES program was originally written to implement the constraint technique only; however, minor modifications will allow PROCES to perform the weighted technique.

To implement the PROCES program the models described in Chapter IV need to be converted to a form usable by a digital computer. The converted models are placed into a subroutine called RESTNT in the form of PI and constraint equations needed for scalar vector optimization. The optimizer subroutine, SUMT, determines optimal solutions for the scalar sub-problem. The scope of the optimization problem was reduced by scaling the performance index equations, and by reducing the dimension of the state variable space. The most profound effects on numerical optimization were realized as a result of reducing the number of state variables.

The results section of this chapter will present the actual benefits derived from these procedures.

5.2.2 Validation. Validation is the process of determining how closely the behavior of a system model approximates the behavior of the real system. The validation task has two purposes. First, to determine the ranges of the state variables, for which the model behaves like the real system. This identifies how well decisions, based on the NDSS, can be expected to perform in real life. Second, the process of validation identifies discrepencies between the model and the real life system, the degree each inconsistancy contributes, and over what ranges of performances these differences occur. This information can be used to put limits on model use, identify impacts of model assumptions, and provide confidence in the answers generated.

No general unifying theory can be used to determine whether or not a model is valid for its intended use. However, a wide range of tools and techniques exist to check the validity of a model and its useful range of application (Kobayashi, 1978: 305). These tools and techniques must be implemented with care. The analyst must keep in mind at all times the intended uses of the model, and the problem under study. This is necessary so that key areas can be validated without wasting excess time and money on areas that are not important. The following checks are used in this study: physical realizability and sensibility, optimality analysis,

and sensitivity analysis.

5.2.2.1 Physical Realizability and Sensibility of NDSS. The realizeability and sensibility checks have no formal or theoretical basis. They are based on logical examination of the model's general behavior. If the model's outputs seem logically unreasonable, it must be determined if the model is wrong and needs revising, if the model is showing real but unexpected results, or if the analytical technique being applied is unsuitable for the model under consideration.

5.2.2.2 Optimality Checks. Optimality checks ensure that with the tools used the solution is optimal and valid. For a non-convex problem, existing search routines can find only locally optimal solutions. For vector optimization a method of checking for optimality should also ensure that the solution is locally noninferior. Direct checks for nondominance (as implemented in the FNSS subroutine of PROCES) ensure that the members of the NDSS are truly nondominated. In addition, optimality checks using Lagrange multipliers provide information on the possible tradeoffs between the performance measures, and the benefits of relaxing constraints.

There are several ways to approach the problem of checking for optimality. Some are mathematically rigorous, but only applicable under a limited set of conditions. Others are more relaxed but applicable over a wider range of

conditions. However, they do not give as much assurance that the NDSS has been found. In this project, both a mathematically rigorous approach and a relaxed approach are used to ensure that the NDSS generated was truly Pareto optimal.

Checking the NDSS against the Kuhn-Tucker Conditions for Noninferiority or KTCN (Chankong and Haimes, 1983: Ch 4, 6) is the mathematically rigorous approach applied. If the objective functions and the constraints are all convex, then the KTCN provide necessary and sufficient conditions for global optimality and noninferiority. Under conditions of nonconvexity, the meaning of the KTCN is harder to interpret, but still provides necessary and sufficient conditions for local noninferiorty. Since noninferior solutions generated by the weighted method are always guaranteed to be members of the NDSS, the KTCN check of these potential solutions become necessary and sufficient conditions to show global noninferiority. Generally the weighted method cannot find all members of the NDSS for a nonconvex problem. For those members of the NDSS which can only be found by the constrained method, the KTCN provides necessary and sufficient conditions for local noninferiority. For the problem formulation of the form defined in section 5.2.1.1 by Eq. (5.1), the KTCN are (Chankong and Haimes, 1983: Ch 4):

1. all $Z_i(X)$ and $G_i(X)$ are differentiable

2. there exists $\lambda_j \geq 0, j=1,..p$, with strict inequality holding for at least one j, and $\mu_i \geq 0, i=1,...,m$, such that

$$G_i(X^*) \geq 0, \quad \mu_i G_i(X^*)=0 \quad (i=1,.....m); \tag{5.11}$$

3. $$\Sigma \lambda_j * \nabla Z(X^*) + \Sigma \mu_i \nabla G_i(X^*) = 0$$

where x* is the potential member of the NDSS. The program PROCES used to generate the NDSS provides estimates of the Lagrange multipliers, (μ_i) for the constraints. These estimates can be used to test the above conditions if there are no pure equality constraints. The λ_j can be determined by numerically estimating the gradients and using least-squares estimation. These estimates of λ_j can be used to show satisfaction of condition (3) above. Next they can be checked against condition (2). If the model satisfies condition (1) then the solution satisfies the KTCN and is locally noninferior.

The second more relaxed method illustrated in Figure 5.9 can be thought of as a filter. For each member of the NDSS, the state variables are individually changed by a small amount, and several tests are made to confirm optimality. The first test checks to see if each of the performance indices becomes optimal as a result of the change. If the performance indices do become optimal, then the second test checks to see if any of the model constraints are violated. If the model constraints are violated, the third test checks the size of the change in the PI values. If the changes are smaller than a specified size, then it is

condidered insignificant. If changes in an NDSS member improve one or all the PIs, do not violate any constraints, and cause significant changes, then it is not an optimal solution, and should not be included in the final NDSS. However, if these changes do not hold, then the NDSS member is a valid noninferior solution.

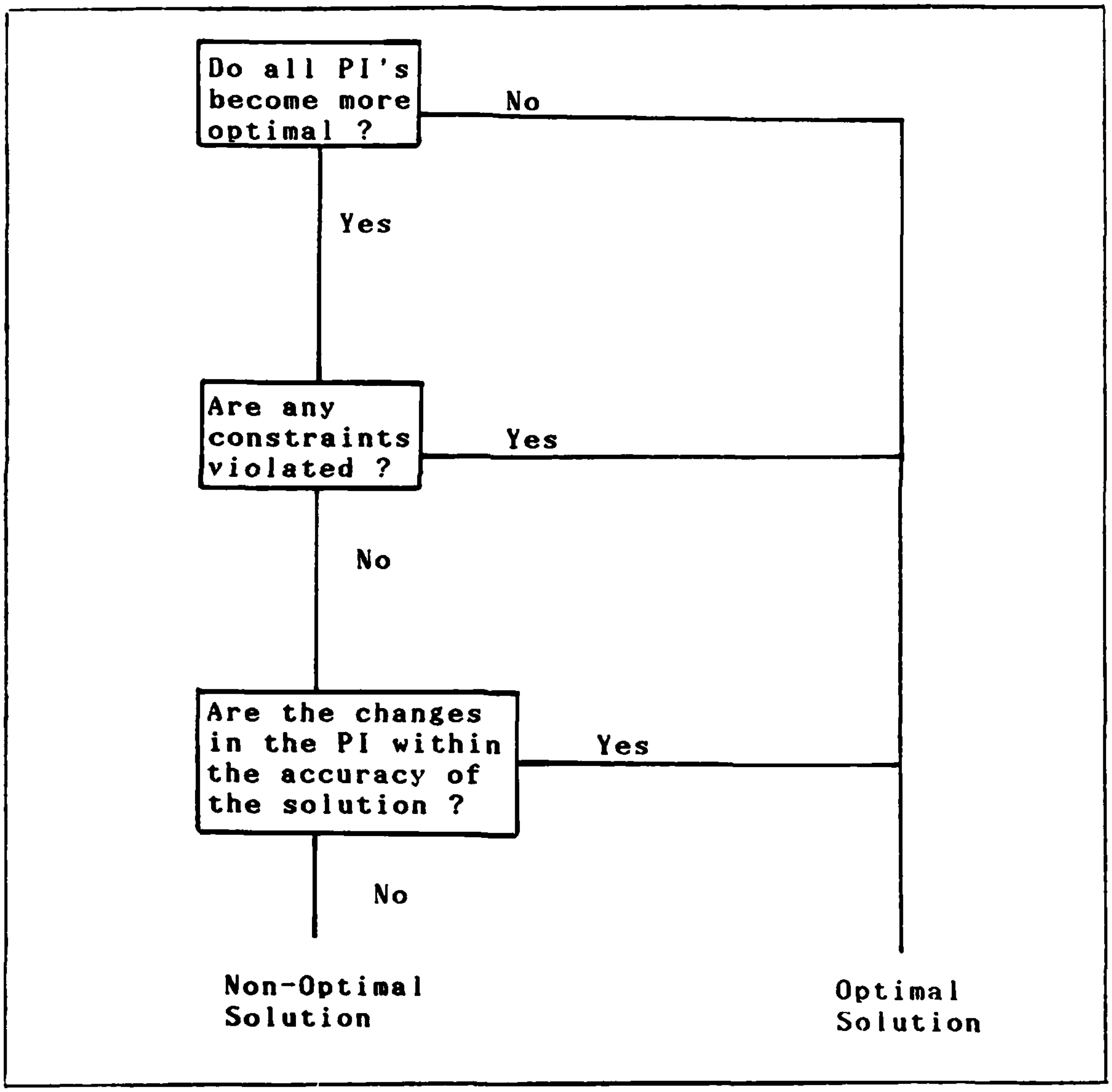

Figure 5.9 Optimality Check Flow Diagram

5.2.2.3 Sensitivity Analysis. Sensitivity analysis identifies the effects of system parameter changes on the nominal solution, and under what circumstances other solutions become optimum. This information provides a feel for how robust the solution is to uncertainties within the model. These uncertainties arise from the assumptions used in building the model. They are found in the model equations and parameter values. These parameter values may be only estimates of the system's true parameter values or they may be chosen to curve fit a particular equation to real system behavior. This means that there is a degree of uncertainty in their values. The spread of this uncertainty represents the model builder's confidence in the assumptions he made. If over the possible ranges of a parameter's values the results are constant or nearly so, then conclusions can be drawn with confidence in their validity. However, if the solution radically changes within the expected range of the parameter, then the suitability to the real environment of the chosen design is less certain. This type of analysis provides information on where the model is solid, and where it is suspect. Two avenues are available; implementation with cautions indicated, or refinement of the model to reduce the uncertainties.

Ideally, sensitivity is performed by varying the model parameters, and all combinations of these parameters, over the expected ranges of the parameter values. With problems

other than the most trivial, the time and effort this takes is not worth the additional information gained. A common procedure is to hold all parameters but one at their expected values, while the other parameter excedes its range of uncertainty. This is done for each parameter which could change. The results are examined to see if the same basic answer occurs for all ranges of the parameter, or for what ranges new types of answers appear. How the results are examined depends on the level of detail in the model. In the early stages of a model analysis, sensitivity can be done by changing the parameters slightly, and reevaluating the PI values for each member of the NDSS. This provides information on which parameters strongly affect the PI values. For later revisions of the model or if large changes in the parameters are examined, then a new NDSS must be generated. Then the NDSS's must be compared to determine the effect of the parameter change.

The sensitivity analysis used has three parts: NDSS sensitivity, model sensitivity, and model sensitivity to large parameter changes. Considerations include identifying variations in a preferred member of the NDSS, due to changes in the states of the system, or changes in the value of an exogenous variable.

5.3 Results

The dimension of a model's state space and its convexity strongly influences the ability of current algorithms to efficiently generate an NDSS. The 21 state variable model developed in Chapter IV to describe a satellite servicing system was reduced to 8 variables because of the excessive computer time required to evaluate this model in its complete form.

Various techniques were tried to reduce the dimension of the state space and allow reasonable solution times. With this reduction the sub-problems converged to 5 digits of accuracy in less than 200 CPU seconds on the CDC Cyber 175. This allowed sufficient iterations of the VOP sub-problems, following the implementation outlined in section 5.2.1.4, to generate the NDSS.

Four state variables were eliminated by the first method, substitution. Model state equations (equality equations) were solved for a state variable, and then were substituted for these state variables wherever they occurred. This eliminates a state variable, while ensuring that the equality equation is satisfied, and is not needed as an explicit constraint. Model Eqs (D.9), (D.23), (D.26), and (D.30) were used to eliminate the following state variables: number of LG launch sites (X320), OSV payload (X510), OSV mission rate (X501), and LG mission rate (X301), respectively

(see Figure 4.14 or Appendix D for equations and Table 4.9 or Appendix E for the state variables). This method of state variable elimination is a standard technique (Wismer and Chattergy, 1978: 57) which ensures implicit satisfaction of the equality equation, while reducing the dimension of the problem.

The second method involves setting state variables to their technological. limits where allowed by model formulation. The state variable for LG structural mass (X325), was eliminated by setting the LG structural mass ratio equal to a constant instead of placing upper and lower bounds on the mass ratio (see Eqs (D.10) and (D.11), Appendix D or Figure 4.14). Setting the mass ratio equal to a constant allows Eq (D.10) to become an equality equation and eliminates Eq (D.11). Then LG structural mass (X325) was eliminated by substitution, as in the first method. The state variable for OSV structural mass (X525) was eliminated the same way as the LG structural mass (using Eqs (D.18) and (D.19)).

The structural mass ratio for the LG and the OSV was set equal to 0.176, as this allows the minimum fuel to achieve a given change in velocity. This was considered a reasonable value as it is within the limits of current technology; there is no cost penalty in the simplified cost estimating relationships for using advanced technology to achieve such low structure ratios. The main loss from the

above two substitutions is elimination of the analyst's ability to evaluate the effect changes in the structural mass ratio had on the individual PI's.

The state variables for LG reliability (X345) and for OSV reliability (X545) were eliminated by setting the reliability equal to 0.90. This value was picked because the PI for initial cost (Z_2) tended to drive this value down, while PI for reliability (Z_3) tended to drive it up. It was felt that reliability for mission accomplishment below this value would be unacceptable for a space system. This action eliminated the need for Eqs (D.13), (D.14), (D.20), and (D.21), the upper and lower bounds on the reliability variable. Setting the LG and OSV reliability equal to a constant eliminates their impact on the initial cost equations for LG and OSV R&D and production costs.

The third method of state variable reduction involved simply setting certain state variables equal to a constant value. By not letting these variables vary over their feasible ranges, information was lost with respect to the effect these variables had on the final solution. Sensitivity analysis (which will be discussed later) will minimize but not eliminate the effect of this loss of information. The constant values are relatively "soft" and should be updated in future refinements of the model.

The constants chosen were based on reasonable estimates

of real system parameter values. LG vehicle down time between missions (X330) was replaced by the constant value 400hrs, which is within the expected range of future launch systems. Time between launches from a specific launch site (X335) was set equal to 14 days, which is an estimate of future launch site turnaround times. The number of LG stages (X370) was set equal to three. This value is in line with past expendable launch systems and larger that the current NASA Space Transportation System (Space shuttle). The LG-OSV rendezvous altitude (X360) was set equal to 200 km. This value was selected because it was felt launch system operating costs would be a major driver in determining the final value of this state variable. Since launch system operating costs increase as altitude increases, a value near the minimal limit seemed appropriate. The number of waiting orbits (X565) was set at two. This value was selected as a reasonable compromise between a low value for short missions (high fuel use), and a higher value for less OSV fuel use (longer missions). Upon making the above simplifications and reductions in the number of state variables the computer program PROCES was run using this model. The approach outlined in section 5.2.1.4 was used to generate an NDSS.

5.3.1 <u>NDSS.</u> Using the approach described in section 5.2.1.4, and the 8-state variable model just described, the program PROCES was used to generate the NDSS. The program was run with 10 starting points using the weighted technique

to get an initial image of the NDSS. The weighted technique generated 15 X-realizations for the NDSS. There were 20 different weights used as shown in Table 5.1, chosen in order to find the full range of the PI values. Using the ranges of the Z_r's found (again see Table 5.1) the program PROCES was run using the constraint technique with 10 starting points. The constraint technique generated an NDSS with 69 distinct X-realizations. This NDSS is presented in Table 5.2. This shows the state vector description for each member of the NDSS. For identification of the meaning of each variable, the reader is referred to Tables 4.9 and 4.11.

Table 5.1

Values of W_r's and Ranges of Z_r's

W_1	W_2	W_3	W_4	W_1	W_2	W3	W_4
1	0	0	0	0.333	0.333	0.333	0
0	1	0	0	0.333	0.333	0	0.333
0	0	1	0	0.333	0	0.333	0.333
0	0	0	1	0	0.333	0.333	0.333
0.5	0.5	0	0	0.4	0.2	0.2	0.2
0.5	0	0.5	0	0.2	0.4	0.2	0.2
0.5	0	0	0.5	0.2	0.2	0.4	0.2
0	0.5	0.5	0	0.2	0.2	0.2	0.4
0	0.5	0	0.5	0.25	0.25	0.25	0.25
0	0	0.5	0.5				

SOL	X300	X301	X310	X320	X325	X326	X330	X335	X345	X360
#	# LG	MIS/YR	KG-P/L	# LS	V MASS	FUEL	T-DAYS	T-DAYS	LG REL	R AL
1	49.50	919.2	54852	35.26	229882	1306146	17	14	0.900	200
2	7.30	155.3	7079	5.95	29664	168544	17	14	0.900	200
3	6.30	134.1	7070	5.14	29625	168326	17	14	0.900	200
4	0.33	6.6	34993	0.25	146773	833939	17	14	0.900	200
5	33.15	649.8	35012	24.92	146728	833681	17	14	0.900	200
6	78.84	1462.8	55205	56.11	231599	1315905	17	14	0.900	200
7	24.31	516.9	7056	19.83	29606	168215	17	14	0.900	200
8	19.41	412.5	7190	15.82	30155	171336	17	14	0.900	200
9	20.03	425.8	7205	16.33	30238	171807	17	14	0.900	200
10	1.01	19.7	34987	0.76	146780	833977	17	14	0.900	200
11	28.83	565.0	35035	21.67	146980	835114	17	14	0.900	200
12	29.18	571.9	35035	21.94	146981	835120	17	14	0.900	200
13	39.65	736.3	54849	28.24	229846	1305946	17	14	0.900	200
14	39.65	736.3	54849	28.24	229846	1305944	17	14	0.900	200
15	39.65	736.2	54850	28.24	229850	1305968	17	14	0.900	200
16	39.88	740.6	54850	28.41	229851	1305973	17	14	0.900	200
17	39.65	736.3	54851	28.24	229853	1305981	17	14	0.900	200
18	39.64	736.2	54851	28.24	229853	1305984	17	14	0.900	200
19	39.65	736.3	54847	28.24	229854	1305987	17	14	0.900	200
20	39.35	730.8	54789	28.03	229857	1306007	17	14	0.900	200
21	38.95	723.5	54794	27.75	229878	1306126	17	14	0.900	200
22	52.02	966.2	54796	37.06	229882	1306150	17	14	0.900	200
23	26.92	554.0	18022	21.25	75521	429099	17	14	0.900	200
24	10.25	200.9	35052	7.71	146395	834629	17	14	0.900	200
25	7.30	143.1	35010	5.4[illegible]	146720	833634	17	14	0.900	200
26	7.33	143.7	35008	5.51	146719	833633	17	14	0.900	200
27	16.26	318.7	350[illegible]	12.[illegible]	146766	833900	17	14	0.9[illegible]	[illegible]
28	34.32	672.6	35015	25.51	146730	833690	17	14	[illegible]	200
29	33.16	650.0	35018	24.9[illegible]	146742	833759	17	14	0.900	200
30	39.55	734.0	551[illegible]	28.[illegible]	231240	1313866	17	14	0.900	[illegible]
31	19.63	364.2	55288	13.97	231951	1317302	17	14	0.900	200
32	[illegible]	363.5	55297	13.94	[illegible]	1318119	17	14	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17	[illegible]	[illegible]	[illegible]
[illegible]	19.55	362.7	[illegible]	[illegible]	[illegible]	1318579	17	14	[illegible]	[illegible]
[illegible]	19.55	362.6	55315	13.[illegible]	232079	1318573	17	14	[illegible]	[illegible]
[illegible]	19.57	362.9	[illegible]	[illegible]	232069	[illegible]	17	14	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17	14	[illegible]	[illegible]
38	19.55	362.7	55303	13.91	232067	1318564	17	14	0.900	200
39	1.52	28.1	55086	1.06	232158	1319079	17	14	0.900	200
40	1.52	28.1	55087	1.08	232158	1319079	17	14	0.900	200
41	39.74	737.7	55037	28.30	230895	1311902	17	14	0.900	200
42	16.72	310.4	54921	11.91	230403	1309134	17	14	0.900	200
43	0.25	4.6	55621	0.18	230324	1308660	17	14	0.900	200
44	59.29	1100.4	55062	42.21	231002	1312509	17	14	0.900	200
45	57.89	1075.1	54798	41.24	229893	1306210	17	14	0.900	200
46	36.44	676.8	54819	25.96	229985	1306735	17	14	0.900	200
47	19.91	369.9	54745	14.19	229671	1304948	17	14	0.900	200
48	19.92	370.0	54738	14.19	229645	1304805	17	14	0.900	200
49	19.87	369.1	54739	14.16	229646	1304805	17	14	0.900	200
50	17.22	319.9	54824	12.27	230002	1306832	17	14	0.900	200
51	17.15	318.6	54813	12.22	230004	1306841	17	14	0.900	200
52	59.72	1108.1	55188	42.50	231531	1315517	17	14	0.900	200
53	58.70	1089.1	55202	41.77	231583	1315811	17	14	0.900	200
54	43.81	816.2	53641	31.31	225028	1278567	17	14	0.900	200
55	42.78	797.0	53638	30.57	225023	1278541	17	14	0.900	200
56	42.63	794.2	53637	30.46	225023	1278539	17	14	0.900	200
57	30.01	559.1	53590	21.45	224821	1277393	17	14	0.900	200
58	28.08	522.3	54304	20.33	227820	1294434	17	14	0.900	200
59	27.91	519.1	54298	19.91	227820	1294430	17	14	0.900	200
60	16.02	298.0	54296	11.45	227787	1294245	17	14	0.900	200
61	14.65	272.5	54294	10.45	227778	1294194	17	14	0.900	200
62	14.30	265.9	54302	10.20	227774	1294169	17	14	0.900	200
63	0.57	10.5	54191	0.40	227589	1293117	17	14	0.900	200
64	137.16	2823.6	17901	108.30	75094	426669	17	14	0.900	200
65	107.68	2218.5	17655	85.09	74072	420866	17	14	0.900	200
66	106.66	2197.3	17652	84.28	74057	420776	17	14	0.900	200
67	94.33	1954.3	17544	74.[illegible]	73603	418201	17	14	0.900	200
68	97.63	2012.0	17553	77.17	73642	418423	17	14	0.900	200
69	93.40	1924.6	17574	73.32	73720	415864	17	14	0.900	200

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Table 5.

NDSS Resu

SOL #	X300 # LG	X301 MIS/YR	X310 KG-P/L	X320 # LS	X325 V MASS	X326 FUEL	X330 T-DAYS	X335 T-DAYS	X345 LG REL	X360 R ALT	X370 STAGES	X500 # OSVs	X501 MIS/YR
1	49.50	919.2	54852	35.25	229882	1306146	17	14	0.900	200	3.0	4.01	534.01
2	7.30	155.3	7079	5.95	29664	168544	17	14	0.900	200	3.0	2.97	98.86
3	6.30	134.1	7070	5.14	29625	168326	17	14	0.900	200	3.0	2.47	78.73
4	0.33	6.6	34993	0.25	146773	833939	17	14	0.900	200	3.0	2.13	10.51
5	33.15	649.8	35012	24.92	146728	833681	17	14	0.900	200	3.0	4.61	2995.89
6	78.84	1462.8	55205	56.11	231599	1315905	17	14	0.900	200	3.0	1.88	871.65
[illegible]	24.31	516.9	7056	19.83	29606	168215	17	14	0.900	200	3.0	5.61	3123.99
[illegible]	19.41	412.5	7190	15.82	30155	171336	17	14	0.900	200	3.0	6.28	3158.68
[illegible]	20.03	425.8	7205	16.33	30238	171807	17	14	0.900	200	3.0	6.46	2998.69
[illegible]	1.01	19.7	34987	0.76	146780	833977	17	14	0.900	200	3.0	4.59	57.34
11	28.83	565.0	35035	21.67	146980	835114	17	14	0.900	200	3.0	6.8	3544.66
[illegible]	[illegible]	571.9	35035	21.94	146981	835120	17	14	0.900	200	3.0	6.25	3474.73
[illegible]	39.65	736.3	54849	28.24	229846	1305946	17	14	0.900	200	3.0	2.46	401.51
14	39.65	736.3	54849	28.24	229846	1305944	17	14	0.900	200	3.0	2.50	401.42
15	39.65	736.2	54850	28.24	229850	1305968	17	14	0.900	200	3.0	2.51	401.48
16	39.88	740.6	54850	28.41	229851	1305973	17	14	0.900	200	3.0	2.45	403.25
17	39.65	736.3	54851	28.24	229853	1305981	17	14	0.900	200	3.0	2.49	401.12
[illegible]	39.64	736.2	54851	28.24	229853	1305984	17	14	0.900	200	3.0	2.48	401.00
[illegible]	39.65	736.3	54847	28.24	229854	1305987	17	14	0.900	200	3.0	2.49	401.27
20	39.35	730.8	54789	28.03	229857	1306007	17	14	0.900	200	3.0	2.49	396.68
21	38.95	723.5	54794	27.75	229878	1306126	17	14	0.900	200	3.0	2.82	402.56
	52.02	966.2	54796	37.06	229882	1306150	17	14	0.900	200	3.0	4.06	564.01
	[illegible]	554.0	18022	21.25	75521	429099	17	14	0.900	200	3.0	1.66	87.38
	10.25	200.9	35052	[illegible]	146395	834629	17	14	0.900	200	3.0	3.96	558.48
	[illegible]	143.1	35010	[illegible]	146720	833634	17	14	0.900	200	3.0	3.21	368.15
	7.33	143.7	35008	5.51	146719	833633	17	14	0.900	200	3.0	3.21	372.21
	16.25	318.7	35018	[illegible]	146766	833900	17	14	0.900	[illegible]	3.0	3.32	865.13
	34.32	672.8	35015	25.61	146730	833690	17	14	0.900	200	3.0	[illegible]	2878.83
	[illegible]	650.0	35018	24.93	146742	833759	17	14	0.900	200	3.0	4.63	3009.29
	[illegible]	734.0	55119	[illegible]	231240	1313866	17	14	0.900	200	3.0	12.52	359.15
	[illegible]	364.2	55289	13.57	231951	1317902	17	14	0.900	[illegible]	3.0	53.77	218.09
	[illegible]	363.5	55297	13.94	231989	1318119	17	14	[illegible]	[illegible]	3.0	[illegible]	240.54
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	362.7	55317	[illegible]	[illegible]	1318575	17	14	[illegible]	[illegible]	3.0	[illegible]	[illegible]
	[illegible]	362.6	55316	13.91	232070	1318578	17	14	[illegible]	[illegible]	3.0	[illegible]	255.56
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17	14	[illegible]	[illegible]	3.0	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	19.55	362.7	55303	13.91	232067	1318564	17	14	0.900	[illegible]	3.0	0.70	255.23
	1.52	28.1	55086	1.08	232158	1319079	17	14	0.900	200	3.0	162.23	657.92
	1.52	28.1	55087	1.08	232158	1319079	17	14	0.900	200	3.0	162.22	657.90
	39.74	737.7	55037	23.30	230895	1311902	17	14	0.900	200	3.0	17.62	273.54
	16.72	310.4	54921	11.91	230408	1309134	17	14	0.900	200	3.0	1.37	109.24
	0.25	4.6	55621	0.18	230324	1308660	17	14	0.900	200	3.0	0.22	0.88
	59.29	1100.4	55062	42.21	231002	1312509	17	14	0.900	200	3.0	6.03	612.44
	[illegible]	1075.1	54798	[illegible]	229893	1306210	17	14	0.900	200	3.0	1.56	588.83
	[illegible]	676.8	54819	25.95	229985	1306735	17	14	0.900	200	3.0	[illegible]	518.13
	[illegible]	369.9	54745	14.19	229671	1304948	17	14	0.900	200	3.0	32.98	133.75
	19.42	370.0	54738	14.19	229645	1304803	17	14	0.900	200	3.0	0.48	133.82
	[illegible]	369.1	54739	14.15	229646	1304805	17	14	0.900	200	3.0	0.47	133.46
	[illegible]	319.9	54824	12.27	230002	1306832	17	14	0.900	[illegible]	3.0	0.47	108.59
	[illegible]	318.6	54818	12.22	230004	1306341	17	14	0.900	200	3.0	[illegible]	108.78
	[illegible]	1108.1	55188	42.50	231531	1315517	17	14	0.900	200	3.0	32.96	279.23
	[illegible]	1089.1	55202	41.77	231583	1315811	17	14	0.900	[illegible]	3.0	1.40	273.76
	43.81	816.2	53641	31.31	225028	1278567	17	14	0.900	200	3.0	1.04	252.38
	42.78	797.0	53638	30.57	225023	1278541	17	14	0.900	200	3.0	0.45	252.49
	42.63	794.2	53637	30.46	225023	1278539	17	14	0.900	200	3.0	0.31	252.94
	30.01	559.1	53590	21.45	224821	1277393	17	14	0.900	200	3.0	1.16	171.05
	28.08	522.3	54304	20.03	227820	1294434	17	14	0.900	200	3.0	0.46	175.47
	27.91	519.1	54298	19.91	227820	1294430	17	14	0.900	200	3.0	0.33	175.71
	16.02	298.0	54296	11.43	227787	1294245	17	14	0.900	200	3.0	1.28	84.50
	14.65	272.5	54294	10.45	227778	1294194	17	14	0.900	200	3.0	0.47	84.41
	14.30	265.9	54302	10.20	227774	1294169	17	14	0.900	200	3.0	0.29	84.25
	0.57	10.5	54191	0.40	227589	1293117	17	14	0.900	200	3.0	0.17	0.69
	137.15	2823.6	17901	108.30	75094	426669	17	14	0.900	200	3.0	0.46	1288.87
	107.58	2218.5	17655	85.09	74072	420866	17	14	0.900	200	3.0	8.19	1016.42
	106.66	2197.3	17652	84.28	74057	420776	17	14	0.900	200	3.0	7.72	991.16
	94.83	1954.3	17544	[illegible]	73603	418201	17	14	0.900	200	3.0	1.71	945.09
	97.53	2012.0	17553	77.17	73642	418423	17	14	0.900	200	3.0	0.48	892.73
	93.40	1924.6	17574	73.82	73720	418864	17	14	0.900	200	3.0	0.47	911.03

X510 PAYLOAD	X525 OSV-MAS	X526 FUEL	X545 REL	X555 #CREW	X560 #SAT	X561 MAS/SA	X565 #V-ORB	Z1 OPS-COST	Z2 $BILLION INTL	Z3 % REL	Z4 K$ #-REL
13670	14194	80650	0.900	0.000	0.090	152081	2	45433.9	85.5	1.000	[illegible]
1943	1463	8310	0.900	4.239	0.486	4001	2	13590.2	19.2	0.999	21.9
2112	1469	8347	0.900	7.846	0.610	3464	2	20227.4	17.0	0.997	19.0
2492	1590	9036	0.900	8.366	4.568	545	2	18037.6	19.2	0.533	5.0
1375	1077	6119	0.900	0.000	0.016	85838	2	20439.4	54.3	1.000	470.3
[illegible]	31527	179132	0.900	0.068	0.055	243516	2	75001.3	114.9	0.987	1334.3
629	92	521	0.900	4.057	0.015	40956	2	25988.3	25.6	1.000	224.4
490	98	554	0.900	0.569	0.015	32227	2	6223.1	26.4	1.000	176.5
535	89	507	0.900	1.213	0.016	31641	2	10557.5	26.2	1.000	173.4
1990	1611	9152	0.900	1.632	0.837	2377	2	8104.6	24.1	0.901	13.0
1117	767	4366	0.900	0.726	0.014	82465	2	22885.1	50.2	1.000	451.8
1125	799	4533	0.900	0.247	0.014	81486	2	19612.8	50.8	1.000	446.2
4552	15123	85927	0.900	0.000	0.120	121727	2	36385.8	74.6	0.997	667.0
4556	15126	85946	0.900	0.001	0.120	121727	2	36388.1	74.6	0.997	667.0
4554	15124	85934	0.900	0.001	0.120	121727	2	36386.7	74.6	0.997	667.0
44[illegible]	15124	85933	0.900	0.005	0.119	121723	2	35612.3	74.8	0.996	667.0
4557	15139	86015	0.900	0.000	0.120	121727	2	36388.0	74.6	0.997	667.0
4571	15142	86036	0.900	0.015	0.120	121728	2	36421.3	74.6	0.997	667.0
45[illegible]	15131	85973	0.900	0.038	0.120	121724	2	36482.8	74.5	0.997	667.0
4523	15152	86090	0.900	0.234	0.121	120923	2	36697.3	73.9	0.997	657.7
4255	14800	84093	0.900	0.340	0.119	[illegible]	2	36713.5	73.4	0.998	655.1
[illegible]613	14099	80109	0.900	0.972	0.085	[illegible]	2	51698.5	86.7	1.000	376.5
[illegible]	17136	97362	0.900	1.052	0.549	[illegible]	2	10745.0	[illegible]	0.978	166.4
[illegible]164	1803	10242	0.900	2.433	[illegible]	[illegible]	[illegible]	15154.6	[illegible]	1.000	[illegible]
[illegible]	1979	11239	0.900	[illegible]	[illegible]	17069	2	4551.1	[illegible]	[illegible]	[illegible]
[illegible]	1970	11194	0.900	[illegible]	0.129	[illegible]	2	4527.4	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	0.900	[illegible]	[illegible]	[illegible]	[illegible]	10214.5	54.4	1.000	[illegible]
[illegible]	1152	6549	0.900	1.300	[illegible]	[illegible]	[illegible]	15462.0	[illegible]	1.000	[illegible]
[illegible]	1067	6060	0.900	0.737	0.016	[illegible]	2	25851.2	[illegible]	1.000	[illegible]
[illegible]	[illegible]	[illegible]	0.900	[illegible]	0.134	121727	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	75612	0.900	[illegible]	0.220	60955	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	60955	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	182500	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	60955	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	60954	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	60955	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	67044	0.900	[illegible]	0.188	60955	2	18104.1	51.5	[illegible]	[illegible]
183	10	56	0.900	0.000	0.073	2514	2	1402.4	45.7	0.970	[illegible]
183	10	57	0.900	0.000	0.073	2507	2	1374.1	45.7	[illegible]	[illegible]
[illegible]	22347	126963	0.900	0.000	0.175	121727	2	36624.6	83.0	1.000	[illegible]
783	20624	117184	0.900	159.491	0.439	60955	2	233602.4	34.5	0.957	[illegible]
537	16297	92597	0.900	155.152	54.516	1092	2	33906.2	[illegible]	0.171	[illegible]
[illegible]	14678	[illegible]	0.900	0.000	0.078	182500	2	54654.2	96.8	1.000	[illegible]
[illegible]	14931	[illegible]	0.900	12.156	0.082	182500	2	76922.8	84.5	[illegible]	[illegible]
277	10567	60037	0.900	23.264	0.093	121728	2	[illegible]	[illegible]	[illegible]	[illegible]
376	22776	[illegible]	0.900	0.000	0.359	60955	2	[illegible]	[illegible]	[illegible]	[illegible]
365	22765	129349	0.900	0.000	0.359	60955	2	18266.0	[illegible]	[illegible]	[illegible]
423	22765	129347	0.900	1.286	0.360	60955	2	18835.8	[illegible]	[illegible]	[illegible]
371	23115	131351	0.900	105.878	0.441	60955	2	65721.3	[illegible]	0.654	[illegible]
296	[illegible]	[illegible]	0.900	[illegible]	0.441	60953	2	51283.2	[illegible]	[illegible]	[illegible]
[illegible]72	[illegible]	137543	0.900	0.000	0.172	182500	[illegible]	55173.8	115.0	[illegible]	[illegible]
[illegible]96	22914	[illegible]	0.900	16.287	0.175	182500	2	77075.9	[illegible]	[illegible]	[illegible]
[illegible]09	23129	131416	0.900	293.453	0.190	182500	2	344500.6	[illegible]	0.909	[illegible]
[illegible]4	23120	131365	0.900	293.482	[illegible]	182500	[illegible]	171641.3	66.5	0.646	[illegible]
[illegible]2	23127	131406	0.900	293.480	0.190	182499	2	129239.2	66.1	0.510	[illegible]
[illegible]	[illegible]	129185	0.900	287.451	0.281	121727	2	[illegible]	53.9	0.931	[illegible]
[illegible]	21776	123726	0.900	288.635	0.274	121727	2	[illegible]	[illegible]	0.652	[illegible]
54	21777	123734	0.900	288.658	[illegible]	121728	2	[illegible]	59.8	0.527	[illegible]
25	23015	130764	0.900	285.771	0.568	60955	2	380230.5	[illegible]	0.947	[illegible]
[illegible]4	23062	131036	0.900	285.610	0.569	60955	2	146290.2	36.3	[illegible]	[illegible]
[illegible]6	23093	131245	0.900	285.529	0.570	60952	2	[illegible]6132.2	[illegible]	[illegible]	[illegible]
[illegible]9	20321	115459	0.900	278.438	69.449	1451	2	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]97	[illegible]	32276	0.900	25.689	0.037	182501	2	57233.3	[illegible]	[illegible]	[illegible]
49	5752	32681	0.900	0.000	0.047	121728	2	35322.8	[illegible]	1.000	[illegible]
[illegible]5	5817	33050	0.900	1.919	0.048	121727	2	49796.9	83.0	1.000	667.0
[illegible]	5237	29754	0.900	21.438	0.051	121727	2	67500.0	66.8	0.780	[illegible]
45	5733	32556	0.900	[illegible]	0.054	121727	2	40358.5	[illegible]	0.667	[illegible]
14	5379	30563	0.900	23.359	0.053	[illegible]	2	41493.6	67.6	0.663	[illegible]

As was discussed in section 4.3.1. a criteria for state variables is that they have a large enough range of values to allow unique descriptions of the design alternatives. Table 5.3 shows the minimum and maximum of each state variable that occured in the NDSS. Each of the 8 state variables ranges over several orders of magnitude. The original variables that were eliminated form the state vector are uniquely determined by these 8 variables. They are presented to give a complete description of the sytems in the NDSS. For example, X-realization #3 might look like Figure 5.10.

Table 5.3

Range of State Variables in NDSS

State Variable	Maximum Value	Minimum Value
Number of MLG'S	137	0.247
MLG Payload (kg)	55620	7056
Mass MLG Propulsion Fuel (kg)	1319690	168000
Number of Satellites Serviced per OSV Mission	69.4	0.0135
Number of OSV's	162	0.1704
Mass OSV Propulsion Fuel (kg)	187500	56.2
OSV Crew Size	293	0.0001
Avg Mass Delivered per Service (kg)	243500	545

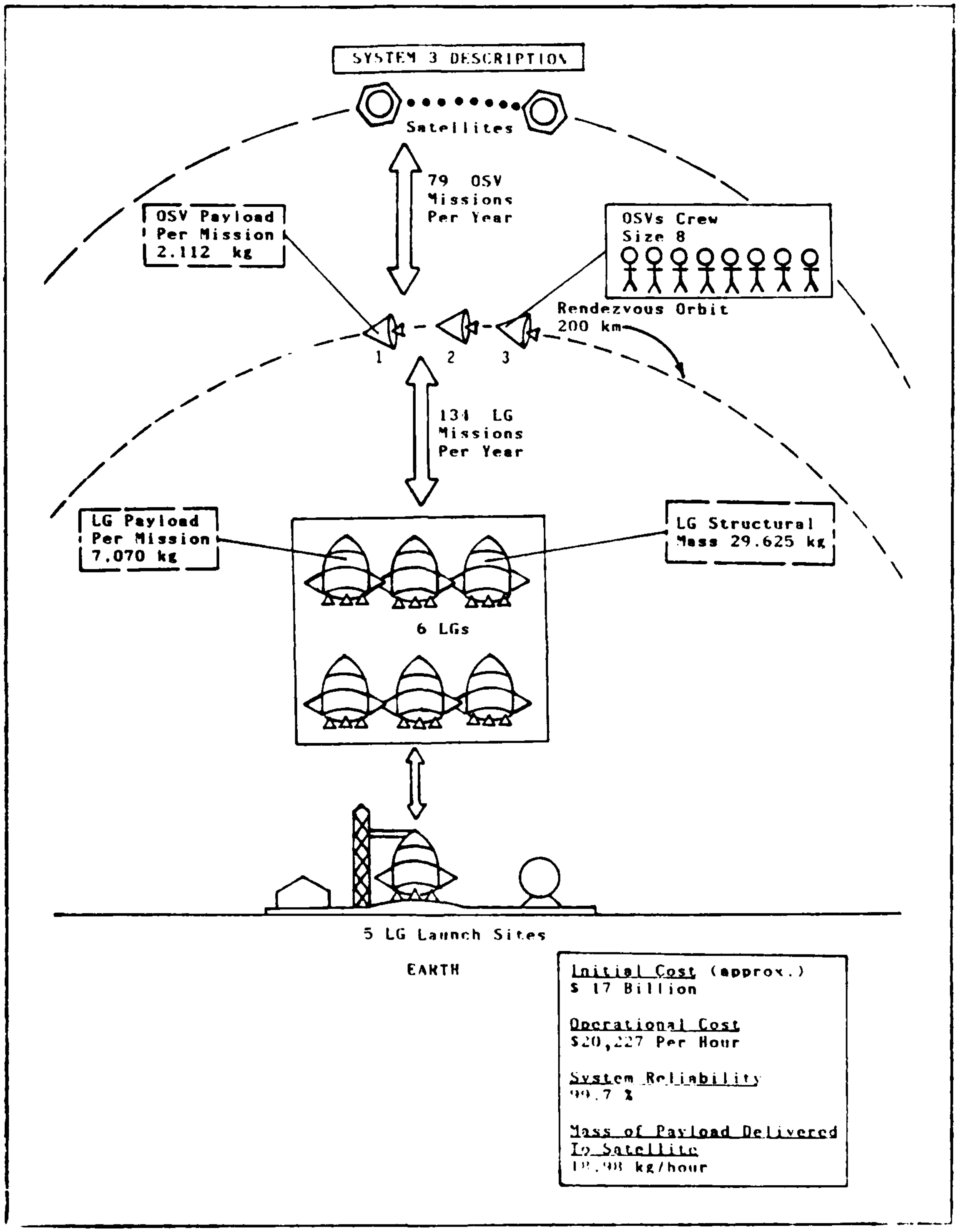

Figure 5.10 System Realization #3

This system has approximately 6 LG's, about half the size of NASA's space shuttle. They perform 134 missions per year from 5 launch sites. The LG supports approximately 2 OSV's each with an 8 man crew. It takes 2 OSV missions to service each satellite with 3500 kg of supplies. The OSV's perform about 79 missions per year.

5.3.2 Validation Results. The validity of the NDSS generated was examined in three ways. First, the range of the state variables was looked at for realizability and sensibility. Second, the optimality of the members of the NDSS was checked to ensure that PROCES had generated a mathematically valid NDSS. Then sensitivity analysis was done to identify which problem factors strongly affected the NDSS, and which parameters strongly affected the model. Sensitivity was also used to check the validity of the techniques used to reduce the dimension of the state vector.

5.3.2.1 Realizability and Sensibility. Table 5.3 also shows that some of the state variables take on values that are unrealistically high, and are probably beyond the range of the simplified model equations.

The Number of LG's (X300) ranges from 0.24 to 137. The realization for the system with one-quarter of an MLG is number 43. This realization has the largest LG payload size and one of the largest structures, about the same size as the Shuttle Derived Vehicles (NASA, 1985: 1-272). The OSV

for this system is large, and not fully utilized, while the mass delivered to each satellite is a modest 1092 kg. The components of this system design are all realistic values within the available technology. This lower bound for X300 is probably a reasonable value if it is interpreted as the part time use of a large LG. The state variable for number of LG's had an upper value of 137 (system 64). This LG has a payload of 18000 kg, making it approximately the size of the shuttle. This number of LG's is probably beyond the range that the cost estimating relationships were designed to handle. In addition, the system requires 108 launch sites. The cost relation for building launch sites is based on only a few sites; this many is again beyond the reasonable application of the relationship. Also, this system delivers over 182501 kg to each satellite every 3 years, far beyond the anticipated needs of satellites for the near future.

The payload mass of the LG (X310), ranges from 7000 kilograms to 55600 kilograms. Associated with this state variable is the fuel mass consumed by the LG, which has a range of 168200 kg to 1320000 kg. This range of values is well within the range of currently exsisting or planned systems (NASA, 1985: 1-249 to 1-282).

The number of OSV's (X500), ranges from 0.17 to 162. The minimum number of OSV's is for system #63. While this many OSV's could be thought of as part-time use of a single

OSV, the size of the OSV needed to perform this mission on a part-time basis is beyond the reasonable bounds of our model. To perform this mission, the OSV must visit over 69 satellites between each reservicing, which is probably beyond the range of our simplified orbital mechanics model. Also, the crew size of the OSV is unrealistically large at over 250 people.

The OSV crew size (X555) ranges from 0.001 persons on board, to 293 people in an OSV crew. The value of 0.001 persons is allowed by our model and simply means that there is really no crew on the OSV. The 293 crew size is not prevented by our model, but life support considerations were based on data for 20 crew members or less. Therefore, crew sizes larger than 20 have rapidly decreasing validity.

The OSV fuel mass consumed per mission (X526) ranges from 56 kg per mission to 187540 kg. The minimum value of 56 kg per mission is associated with system 39, which has a value for number of satellites visited per mission of 0.07. This is not a realistic value for number of satellites visited per mission. It allows unrealistically low estimates of OSV fuel needed per mission. The maximum value of OSV fuel consumed, 187540 kg, is associated with system 52, and while it is realistic from an engineering point of view, the payload delivered per satellite service is over 183000 kg. This is probably far beyond the needs of current, or envisioned future systems.

The number of satellites serviced per OSV mission, X560, ranges from a low of 0.01 to a high of 69.4 satellites serviced per OSV mission. In reality, this should be an integer value, but this is not allowed by our analysis techniques. An approximation with real numbers was used. This was valid for some of our equations dealing with mass delivered or used by the various subsystems. However, the equation determining the OSV fuel requirements (Eq (D.22)) is invalidated as this variable takes on values less than one. The high value of 69.4 is within the reasonable range as the orbital mechanics is concerned, but since it is associated with, system 63, it is already invalidated due to the extreme size of the OSV.

The mass delivered for service to each satellite in each three year service interval (X561) ranges from a high of 243000 kg to a low of 545.5 kg. The high value of 243000 kg is delivered by system 6, which is sized sufficiently large to deliver such a mass, but this mass is probably far beyond what any satellites currently envisioned might need. The bottom of the range 545.5 kg is large enough to serve smaller satellites, or large satellites with minimal service needs.

5.3.2.2 Optimality Check Results. The optimality of the NDSS was tested by the methods discussed in section 5.2.2.2. Results showed that in spite of the nonconvexity of this model, the NDSS generated was Pareto optimal.

5.3.2.3 Sensitivity Analysis. The results of the sensitivity analysis will now be presented in three parts. First, the sensitivity of the NDSS, second, the model sensitivity and third, the effect of large changes in the model parameters on the NDSS.

5.3.2.3.1 NDSS Senitivity. Sensitivity was performed on the entire NDSS. To give more meaning to the results a subset of the NDSS will be evaluated. This subset of the NDSS is identified in Chapter VI (Decision Making). It consists of members ranked highly across a broad range of decision maker's preferences. Each state variable of the reduced model will be evaluated separately. The PI's which are affected will be identified, and the magnitude of the effects will be shown. For each of the NDSS members, the eight state variables(SV) were changed in increments of 2,4,6,8 and 10 percent.

The data which appears in Table 5.4 for each PI is for 10 percent changes in the state variables. The columns under each state variable contain five numbers. The first entry is the actual value of the SV, the second through the fifth entries are the percent change in the PI's. For example, solution number two has variable X300, equal to 7.3. The operations cost sensitivity to a 10 percent change in X300 is 0.577 percent. The initial cost had a sensitivity of 1.45 percent for a 10 percent change in X300. The reliability sensitivity was 0.0001 percent for a 10 percent

change in X300, and there was no significant change for mass delivered per hour sensitivity analysis.

Table 5.4

NDSS Sensivivity to Changes in X Values

SOL#		X300	X310	X326	X560	X500	X526	X555	X561
PI	VALUE	VALUE % chg	VALUE % CHG	VALUE X1000 % CHG	VALUE % CHG	VALUE % CHG	VALUE % CHG	VALUE % CHG	VALUE % CHG
#2		7.3	7079	168.5	0.486	2.97	8310	4.24	4000
OPS	13590	0.577	-0.154	0.702	-0.02	9.25	0.022	9.25	
IC	192	1.45		2.06		0.333	0.172	-1.25	
REL	0.999	0.0001				0.053			
MD	21.9								10.0
#3		6.3	7070	168.3	0.609	2.47	8346	7.85	3461
OPS	20227	0.419	-0.001	0.407	-0.01	9.56	0.01	9.56	
IC	171	1.42		2.20		0.351	0.112	-1.46	
REL	0.996	0.0001				0.148			
MD	19.0								10.0
#6		78.8	55204	1315	0.055	1.88	179132	0.088	243515
OPS	73000	9.23	-1.33	9.19	-0.678	0.022	0.746	0.022	
IC	1149	6.81		4.35		0.101	0.242	-0.014	
REL	0.987					0.466			
MD	1334.0								10.0
#7		24.3	7055	168.2	0.0154	5.609	521	4.057	40955
OPS	25988	1.25	-0.027	1.22	-0.021	8.72	0.023	5.23	
IC	256	3.31		2.87		0.38	0.013	-0.805	
REL	0.999					0.001			
MD	224.0								10.0
#8		19.4	7189	171.3	0.0152	6.28	554	0.569	32227
OPS	6228	4.22	0.092	4.103	-0.093	5.68	0.012	5.68	
IC	265	2.63		2.44		0.342	0.024	-0.181	
REL	0.999					0.0001			
MD	177.0								10.0
#9		20	7205	171.8	0.016	6.46	507	1.213	31641
OPS	10557	2.58	-0.056	2.51	-0.047	7.36	0.05	7.36	
IC	262	2.74		2.52		0.367	0.2	-0.355	
REL	0.999					0.0001			
MD	173.0								10.0

X300- # of LG systems
X310- Payload mass per launch (Kg)
X326- Mass of LG propulsion fuel (Kg)
X500- # of OSVs
X526- Mass of OSV propulsion fuel (Kg)
X555- OSV crew size
X560- # sat. serviced/OSV mission
X561- Ave mass delivered to a sat (Kg)
MD = Mass Delivered/Hr (Kg/Hr)

OPS = Operating Costs/Hr ($/Hr)
IC = Initial Costs ($ x100000000)
REL = Reliability
MD = Mass Delivered/Hr (Kg/Hr)

All numbers represent the 10% change level of the state variables.

The sensitivity data presented in Table 5.4 is used to interpret the validity of the NDSS. The number of LG's (X300) affects the NDSS in two of the four PI's , operations cost and initial cost. The operations cost is more sensitive across the NDSS with a range of sensitivity between 9.23 percent to 0.419 percent for solution numbers 6 and 3 respectively. In the original model, the number of LG's did not appear in the equation for operations cost. Operations cost is affected in the reduced model because the equality constraints were used to substitute this variable into the operations cost equation. The initial cost sensitivities range from 6.81 percent to 1.42 percent for solutions six and three respectively. The payload mass of the LG (X310) has indirect impact on all of the PI's through the constraint (Eq(D.29). This constraint requires that the total mass of the LG system must be off loaded by the OSV fleet. The mass of the LG propulsion fuel (X326) affects operations cost and initial cost. The sensitivity of operations cost ranges from 0.407 percent to 9.19 percent for solutions three and six respectively. The initial cost range sensitivity is 2.20 percent to 4.35 percent for solutions three and six respectively. The number of OSV's (X500), effects initial cost, reliability and operations cost. The intial cost and reliability are relatively insensitive when compared with operations cost. They have a sensitivity range of 1.8 percent to 9.56 percent for solutions numbers six and three. The NDSS is insensitive to small changes in the mass

of the OSV propulsion fuel (X526). The OSV crew size (X555) affects the operations cost and initial cost PI's. Operations cost has a sensitivity range of -0.022 percent to 9.56 percent for solution numbers six and three. Initial cost sensitivity ranges from -0.014 percent to -1.46 percent for solution numbers six and three respectively. The NDSS is insensitive to the number of sattellites serviced per OSV mission (X560). However, the entire NDSS is critically sensitive to any variation in the mass delivered per hour (X561). Mass delivered, the fourth PI, will proportionately follow any change in X561.

The solutions that were most sensitive to variations in the state variables are solution numbers six and three. These two systems appear to be almost opposites in terms of their physical descriptions. System number six delivers an extreme amount of mass (1334 KG/Hr) to a satellite constellation, whereas system three is more resonable with an 18 Kg/Hr rate. The more nominal solutions (numbers 7,8,9) have average sensitivities to the PI's, and thus appear to have more stable operating points. The sensitivity of the operations cost tends to rise as the size of the system increases. This phenomenon is counter to the logic that if more systems are being used, and if one subsystem is lost the impact should be less. Upon closer examination of the operations cost equations, it can be seen that it is quadratic with respect to the number of LG launch systems

(X300) and payload mass per launch (X310). Sensitivity of these two parameters is intimately tied to each other. The mass delivered per hour is extremely sensitive to mass delivered per satellite service (X561). Also, the greater the amount delivered to a satellite at each visit, the greater the total mass delivered to the constellation of satellites. In choosing a system to be implemented, this table can aid the decision-maker in determining which aspects of the design to most carefully monitor. For example, in implementing system number 8, operations cost be lowered with little or no effect on initial cost by changing the OSV crew size (Table 5.4).

5.3.2.3.2 Model Sensitivity. Determining under what conditions the model is valid can be accomplished by looking at the local sensitivities of the exogenous variables of the model; enviroment, structural and substituted state variables. The enviromental parameters define the conditions under which the model must function. An example would be the number of satellites to be serviced. The structural parameters are the assumptions used to define coefficients of terms in the PI's and the constraint equations. While some of these values are known very accurately, others may may be very crude estimates. As an example, the value of the earth's gravitational constant is well known but the exogenous variable for cost/unit of OSV fuel (U22) is somewhat arbitrary. Substituted state variables should be

evaluated to determine the impact of having fixed values.

Table 5.5 is similar to Table 5.4 except that the exogenous variables are changed one at a time. For solution number 2 the operations cost had a value of $13590 and had a sensitivity of 0.022 percent for a 10 percent change in the value of U2. Model sensitivity more readily displays sensitivity trends between the performance indices. Table 5.5 and Table 5.4 both use the same NDSS members making comparisons possible. However, Table 5.5 only contains entries for those exogenous variables that produced a greater than 0.01 percent change in a PI for a corresponding 10 percent change in the exogenous variable.

These enviromental parameters, the number of satellites (U2) and the satellite service interval (U3), produce a 10 percent change in mass delivered for a corresponding change in their values. Although the model is most sensitive to these two variables, this is insignificant since the entire NDSS is equally affected. Due to the fact that the PI equations were derived to show relative differences and not absolute values, the result is a shifting of the NDSS along the Z_4 (mass delivered) axis of the Z_p space (performance index space).

The substituted state variables are insensitive in comparison to the values obtained in Table 5.4 . Their moderate values of sensitivity validate their use as constants.

Table 5.5

Substituted State and Enviroment Exogenous Variables Sensitivities

SOL#		U2	U6	X330	Note 1	Note 2
PI	VALUE	VALUE % chg 144	VALUE % CHG 26280	VALUE % CHG 400	VALUE % CHG 0.176	VALUE % CHG 0.176
#2						
OPS	13590	0.022	-0.02	-0.639		
IC	192				2.069	0.171
REL	0.999					
MD	21.9	10.0	-9.09			
#3						
OPS	20227	0.0118	-0.01	-0.371		
IC	171				2.20	0.112
REL	0.996					
MD	19.0	10.0	-9.09			
#6						
OPS	73000	0.746	-0.678	-7.21		
IC	1149				4.354	0.2417
REL	0.987					
MD	1334.0	10.0	-9.09			
#7						
OPS	25988	0.023	-0.021	-1.12		
IC	256				2.87	0.013
REL	0.999					
MD	224.0	10.0	-9.09			
#8						
OPS	6228	0.102	-0.092	-3.73		
IC	265				2.44	0.024
REL	0.999					
MD	177.0	10.0	-9.09			
#9						
OPS	10557	0.522	-0.0475	-2.29		
IC	262				2.52	0.020
REL	0.999					
MD	173.0	10.0	-9.09			

U2 - # of satellites
U6 - Satellite service interval (Hr)
x330- Average time between missions/LG (Hr)
Note 1 - This is the mass ratio of the LG structure/fuel
Note 2 - This is the mass ratio of the OSV structure/fuel
OPS = Operating Costs/Hr ($/Hr)
IC = Initial Costs ($ x100000000)
REL = Reliability
MD = Mass Delivered/Hr (Kg/Hr)

All numbers represent the 10% change level of the exogenous variables.

The structual variables of the models that caused a greater than one percent change in a PI as a result of a ten percent change in the structual variable are entries in Table 5.6.

Table 5.6

Structural Exogenous Variable Sensitivity

SOL#		U29	U30	U37	U38	U79
PI	VALUE	VALUE % chg 1.25	VALUE % CHG 1.3	VALUE % CHG 1.25	VALUE % CHG 1.3	VALUE % CHG 125000
#2 IC	192	2.10	2.10	5.97	5.97	10.0
#3 IC	171	1.36	1.36	6.71	6.71	10.0
#6 IC	1149	0.996	0.996	1.51	1.51	10.0
#7 IC	256	1.52	1.52	4.48	4.48	10.0
#8 IC	265	2.43	2.43	4.35	4.35	10.0
#9 IC	262	2.23	2.23	4.40	4.40	10.0

U29 - OSV technical development factor
U30 - OSV R&D team experiance factor
U37 - LG technical development factor
U38 - LG R&D team experiance factor
U79 - Cost/man-year cost equations
IC = Initial Costs (\$ x100000000)

All numbers represent the 10% change level of the exogenous variables.

Initial cost is the only PI affected by small changes in these exogenous variables. The cost/man-year (U79) has the greatest impact on the initial cost. Examination of the

equation governing the initial cost (Appendix D, Eq (D.2)) revealed that U79 is a common factor in every term of the equation, thus explaining its high sensitivity. Even though the cost/man-year is sensitive, it can be accuratly predicted, thus reducing its impact. Changes in U79 results in a linear translation of the NDSS space along the initial cost axis. The size and shape of the Z space does not change; however, its location is changed.

Small changes in the remaining four exogenous variables affect the R&D portion of the initial costs in the same magnitude, although they have less impact on total initial cost as the number of LG and OSV units purchased increases. Thus initial costs are affected by the number of units purchased, but R&D costs are not. For example, system number six in Table 5.6 is less sensitive than system number three to changes in the variables.

5.3.2.3.3 Large Model Parameter Changes. The equality constraints (Eq (D.15), Eq (D.22), and Eq (D.28) of Appendix D) such that the capacity of one subsystem equals the need of another. For example, Eq (D.15) requires that the MLG be capable of reaching the LG-OSV rendezvous orbit. Large changes in the exogenous variables cause the constraints to be violated for particular members of the NDSS. For some members, the sub-systems will then have either excess capacity or excess need. When the NDSS is re-optimized to satisfy these constraints, changes in its members can be

predicted. To predict how large changes in the values of the exogenous variables would change the NDSS, they were varied over their full range. The direction of constraint violation was examined to get an indication for how the NDSS might change. The results of this check are in Table 5.7.

Eq (D.15) constrains the LG to have sufficient capability to reach the LG-OSV rendezvous altitude. When this constraint is violated on the excess capacity side, the member's of the NDSS generated could be expected to use smaller or fewer LG's. It would also be expected to have lower costs for the same system performance. When this constraint is violated on the side of excess requirement, then the members of the NDSS change in the opposite manner. If this constraint is violated far enough, then there might be no feasible LG realization.

Eq (D.22) constrains the OSV to have sufficient fuel capacity to perform its mission. It influences the OSV in a similar manner as Eq (D.15) influences the LG. In addition, this change causes a reduction in number or size of the LG's. Consequently, the systems initial and operating costs are reduced for the same system performance. Violation of this constraint on the side of excess requirement would have just the opposite affect on the resulting NDSS.

Table 5.7

Effect of Exogenous Variable Changes on Constraints

Exogenous Variables: Name and Nominal Value (N.V.)	Direction of Change	Constraints: LG ΔV Rqr'd ΔV to Rendezvous with OSV: Excess Capacity	LG ΔV Rqr'd ΔV to Rendezvous with OSV: Excess Requirement	OSV ΔV Capacity OSV Mission ΔV: Excess Capacity	OSV ΔV Capacity OSV Mission ΔV: Excess Requirement	LG launch Capacity, OSV needs + Sat needs: Excess Capacity	LG launch Capacity, OSV needs + Sat needs: Excess Requirement
Average Sat Altitude N.V. = 800 km	Above N.V.				X		
	Below N.V.			X			
# of Sats N.V. = 144	Above N.V.				X		X
	Below N.V.			X		X	
Sat Service Interval N.V. = 3 yr	Above N.V.					X	
	Below N.V.						X
LG-OSV Mass Transfer Rate N.V. = 800 kg/hr	Above N.V.					X	
	Below N.V.						X
LG Fuel Isp N.V. = 400 sec	Above N.V.	X					
	Below N.V.		X				
Baseline OSV L.S.E.Mass N.V. = 2432 kg	Above N.V.				X		
	Below N.V.			X			
OSV L.S.E. Coeff N.V. = 305kg/person	Above N.V.				X		
	Below N.V.			X			
OSV L.S. Expendables N.V. = 0.64 kg/person-hr	Above N.V.						X
	Below N.V.					X	
OSV Crew Rotation Time N.V. = 90 days	Above N.V.					X	
	Below N.V.						X
OSV Guidance Eqpt Coeff N.V. = 200 kg	Above N.V.				X		
	Below N.V.						
OSV Resupply Parts/Mission N.V. = 100 kg	Above N.V.						X
	Below N.V.					X	
OSV Fuel Isp N.V. = 500 sec	Above N.V.		X				
	Below N.V.	X					
LG Turnaround Time N.V. = 17 days	Above N.V.						X
	Below N.V.					X	
Rendezvous Altitude N.V. = 200 km	Above N.V.	X		X	X		
	Below N.V.		X				
# of LG Stages N.V. = 3	Above N.V.	X					
	Below N.V.		X				
LG Mass Structure Ratio N.V. = 0.176	Above N.V.		X				
	Below N.V.	X					
# of OSV Waiting Orbits N.V. = 5	Above N.V.				X		
	Below N.V.			X			
OSV Mass Structure Ratio N.V. = 0.176	Above N.V.				X		
	Below N.V.			X			

Notes: ΔV = Delta Velocity; L.S. = Life Support; L.S.E. = Life Support Equipment; Sat(s) = Satellite(s)

The LG delivery capacity is constrained to be large enough to deliver the needs of the OSV and the satellites to the rendezvous altitude by Eq. (D.28). If this constraint is violated on the side of excess LG capacity, then again, as for Eq (D.15), the new NDSS will have fewer or smaller LG's to maintain the same capacity. If it is violated on the side of excess OSV or satellite needs, then the NDSS will need more and larger LG's, or will have less system performance.

5.4 Summary

In this chapter we have shown that for a large multiobjective problem, a set of optimal engineering solutions can be generated. These solutions provide the decision maker with a set of Pareto optimal solutions. In Chapter VI, the value system will be used to aid the decision maker in selecting the most preferred system from among the candidate solutions in the NDSS.

The validity analysis highlighted the following important characteristics of the model.

1. The performance measures are most strongly affected by the two exogenous control variables: number of satellites in the constellation to be serviced and the satellite service interval.

2. The equality constraint requiring the total LG payload to be off-loaded to the OSV fleet is the primary binding constraint. This indicates that an intermediate drop point (SB) may be beneficial.

3. The experience factor of the design and construction teams has a strong effect on the value of the cost PIs.

Some good solutions were generated; however, the simplifications in this model allowed many that were invalid. To correct these problems, future iterations of the model need the following areas of refinement.

1. The state variable for the number of satellites serviced per OSV mission (X560) invalidates the equation for determining OSV fuel requirements (Eq (D.22)) when it has a value less than one. However, in equations involving things such as mass needed or mass delivered (Eqs (D.23), (D.24), (D.26), and (D.28)), it is desirable to allow this variable to have values less than one. Setting X560 equal to a value of one only in Eq (D.22), when it actually has a value less than one, will produce the desired results in the model and eliminate inconsistencies.

2. Refine the equations that define the life support requirements on an OSV, or limit the crew size to the model range of less than 20 people.

3. Refine the relations that represent the tradeoffs between performing the servicing with higher levels of automation (unmanned) versus manned techniques.

4. The current model only examines relative costs for comparative purposes, and does not yield total costs for the systems (see Chapter IV). Improve the cost estimating equations to allow their use to predict total versus relative costs.

VI. Decisionmaking

6.1 Introduction

The first phase of the systems engineering approach has been completely described in the preceding chapters. The problem was defined, the problem boundaries and assumptions were established, and a candidate architecture was proposed and modeled. The model was then ranged iteratively over its design space to yield a set of non-dominated solutions (NDSS) that were optimal from a design viewpoint.

This same procedure is followed for every candidate architecture. The non-dominated solution set for each candidate is usually then combined into a single set. Each element of the non-dominated solution set represents a different system that offers the most efficient performance measures for its design. This combined set should have each of its elements crosschecked against the others for non-dominance, and each dominated solution should be eliminated.

As demonstrated in the last chapter, there were 69 different choices in the NDSS for that one candidate architecture. If five different architectures were being considered, the NDSS might include as many as 350 possible solutions. An analyst should not bring a list of 350 solutions to a decision maker for him to choose among. That amount of information would be overwhelming, and it would require an extraordinary amount of time for the decision

maker to review the results.

The second phase of the systems engineering approach eliminates this inefficiency. In the second phase, a value system is designed that allows the analyst to capture the preferences of the decision maker in an efficient and repeatable manner. Solicitation of the decision maker's preferences by the analyst requires only a small time investment early in the design process. This solicitation session provides all the information necessary for the analyst to design a value system that represents that decision maker's preferences. Chapter III showed how an analyst then uses this value system to create a weighted hierarchy of objectives for determining a single figure of merit for each system in the NDSS. The figure of merit is a scalar index that represents the decision maker's preferences for a system. The solution in the NDSS with the largest figure of merit is then the most preferred solution based on the decision maker's initial preferences. Now it is possible for the analyst to bring a list of solutions to the DM that have already been ranked by the DM's own preference structure. This is a time-efficient method for both the analyst and the decision maker. The value system framework thus enables the decision maker to view the optimal choices with their advantages and disadvantages. This approach has the benefit of traceability for any decision made. Since there is written documentation showing the ranked solutions based upon par-

ticular preferences, a decision can be reviewed at any time, and changed if conditions warrant it. In addition, if the preferences change for any reason, the first phase of the methodology does not require reaccomplishment. The original NDSS is still valid. With the new preferences incorporated in a value system, a revised ranking of solutions can be quickly obtained.

6.2 Ranking the NDSS for a Satellite Servicing System

This section describes how value systems were constructed for several decision makers, and used to rank an NDSS for a candidate satellite servicing system.

The hierarchy of objectives in Figure 6.1 was shown to senior USAF decision makers from the USAF Space Division, the USAF Satellite Tracking and Control Facility, and NASA (Carlton, 1985; Crabtree, 1985; Green, 1985; Hard, 1985; Janson, 1985; Lemon, 1985; Sundberg, 1985; Wimberly, 1985; Wittress, 1985; Zersen, 1985). Pairwise comparisons between the objectives were solicited from the decision makers in personal interviews, using the procedures described in section 3.3.

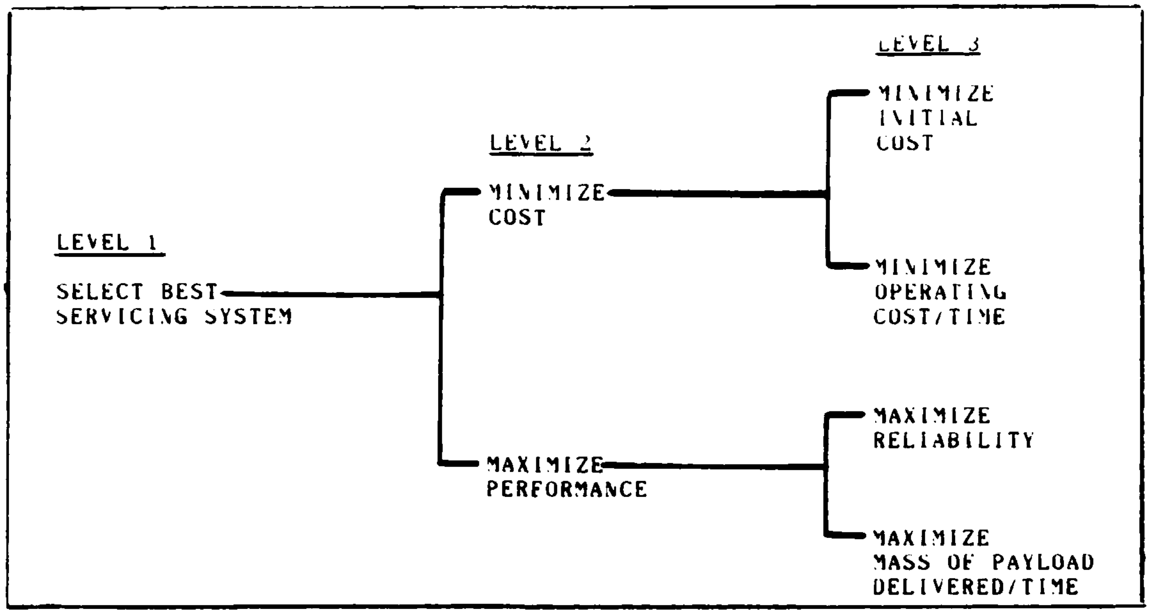

Figure 6.1 Hierarchy of Objectives

Using the Saaty eigenvalue/eigenvector approach as described in section 3.3, normalized eigenvectors were found for the pairwise comparison matrices; the resulting weightings for one of these decision makers are shown on the tree in Figure 6.2.

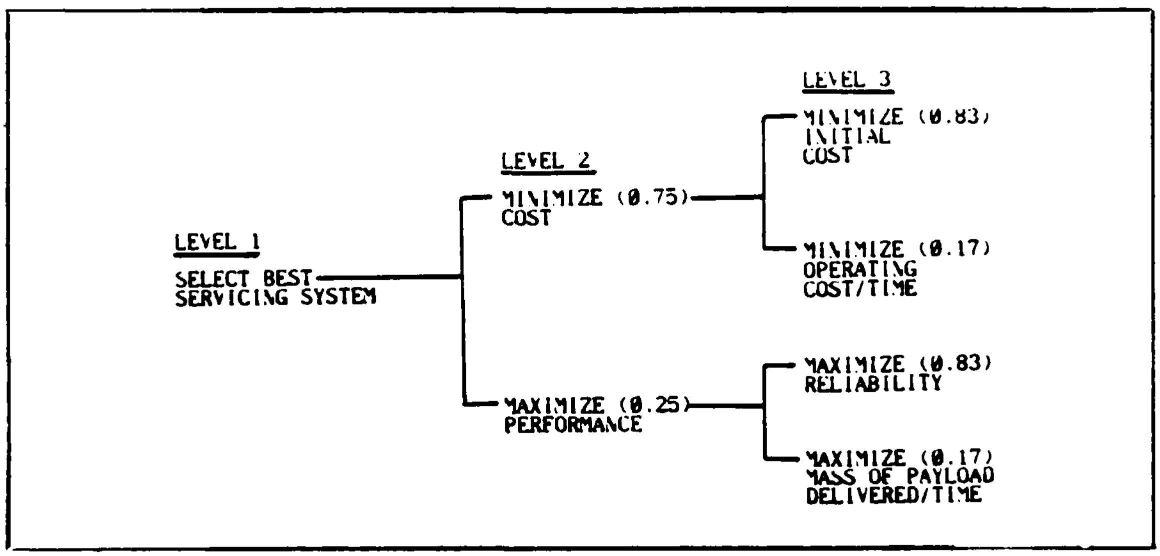

Figure 6.2 Weighted Hierarchy Tree

Multiple objective optimization techniques were used on a model for a system of low-G launchers and orbital servicing vehicles to obtain the NDSS shown in Table 6.1.

For simplicity in this example, linear value functions were used to demonstrate the decision maker's preferences over the ranges of the performance index measures. Table 6.2 shows the resulting "values" for the performance indicies of each candidate solution. When these values are multiplied by the weights in the hierarchy tree and summed, a scalar figure of merit is obtained for that candidate solution. The 69 candidate solutions in the NDSS are ranked based on their individual figures of merit as shown in Table 6.3. Note that this ranking is valid only for this particular decision maker, since it is based on his preference structure alone.

Table 6.4 shows the tree weightings and rankings for nine additional USAF decision makers who were interviewed. Note that the members of the NDSS are ranked differently for every decision maker, since each decision maker preferred slightly different objective weightings. This example used the same linear value functions for each decision maker. If different value functions had been obtained from each decision maker for each performance measure (see section 3.4.1), the differences in rankings might have been much greater. This example emphasizes the reason for including the decision maker's value system in a methodology. When a large

set of optimized candidates have been generated, the value system provides an organized and time-efficient way for the decision maker to determine his preferred solution.

Table 6.1

Non-dominated Solution Set

SYS	OPS COST ($/hr)	INITIAL COST ($)	RELIABILITY (0 to 1)	MASS P/L DELIV (kg/hr)
1	.454338594e+05	.855085138e+11	.999902070e+00	.833318176e+03
2	.135902100e+05	.192213197e+11	.998936057e+00	.219222889e+02
3	.202274492e+05	.170900193e+11	.996610284e+00	.189814091e+02
4	.180376289e+05	.192244695e+11	.533011556e+00	.298893189e+01
5	.204594492e+05	.543327560e+11	.999975443e+00	.470345581e+03
6	.730013359e+05	.114985394e+12	.986938298e+00	.133433398e+04
7	.259882988e+05	.256055788e+11	.999997497e+00	.224415390e+03
8	.622812256e+04	.264570696e+11	.999999464e+00	.176584595e+03
9	.105575293e+05	.262032384e+11	.999999642e+00	.173377686e+03
10	.810460791e+04	.241938084e+11	.901215792e+00	.130233393e+02
11	.228850781e+05	.502224978e+11	.999999762e+00	.451818390e+03
12	.196127793e+05	.508876595e+11	.999999344e+00	.446176086e+03
13	.363857578e+05	.746294067e+11	.996550798e+00	.666999939e+03
14	.363880586e+05	.746435789e+11	.996818841e+00	.666997253e+03
15	.363867070e+05	.746511483e+11	.996940494e+00	.666999573e+03
16	.366123086e+05	.748690555e+11	.996483088e+00	.667001343e+03
17	.363879961e+05	.746475438e+11	.996766984e+00	.667000183e+03
18	.364213281e+05	.746142024e+11	.996651947e+00	.667002686e+03
19	.364827695e+05	.745830318e+11	.996765494e+00	.666978394e+03
20	.366973477e+05	.739559260e+11	.996756971e+00	.657660950e+03
21	.367135078e+05	.734554849e+11	.998473763e+00	.655064941e+03
22	.516985469e+05	.867065692e+11	.999913096e+00	.876479187e+03
23	.107450498e+05	.407922196e+11	.978301167e+00	.166442490e+03

Table 6.1 (continued)

SYS	OPS COST ($/hr)	INITIAL COST ($)	RELIABILITY (0 to 1)	MASS P/L DELIV (kg/hr)
24	.161646494e+05	.323950899e+11	.999889791e+00	.137975296e+03
25	.455112354e+04	.318813389e+11	.999389291e+00	.935293274e+02
26	.452737354e+04	.319199191e+11	.999389291e+00	.942290649e+02
27	.402145391e+05	.344222188e+11	.999517441e+00	.240106094e+03
28	.284619883e+05	.537167462e+11	.999948084e+00	.499082275e+03
29	.238811797e+05	.536174961e+11	.999976754e+00	.479951996e+03
30	.364954180e+05	.793251267e+11	.999999940e+00	.666999939e+03
31	.181679785e+05	.707025060e+11	.999999940e+00	.333999695e+03
32	.181334883e+05	.653597573e+11	.999999940e+00	.333999969e+03
33	.128944797e+06	.662309888e+11	.907147348e+00	.999998779e+03
34	.180940586e+05	.516531896e+11	.803135395e+00	.333998688e+03
35	.181072598e+05	.516100383e+11	.803070366e+00	.333996582e+03
36	.181062383e+05	.516681359e+11	.803124368e+00	.333999786e+03
37	.181074590e+05	.516657193e+11	.802892089e+00	.333999084e+03
38	.181040684e+05	.516382966e+11	.802072167e+00	.333999969e+03
39	.140240894e+04	.457511363e+11	.969539344e+00	.137747498e+02
40	.137405798e+04	.457504399e+11	.969515681e+00	.137357197e+02
41	.366246172e+05	.830225285e+11	.999999940e+00	.666999939e+03
42	.233602391e+06	.396003369e+11	.957209945e+00	.333999878e+03
43	.339061875e+05	.183158292e+11	.170653790e+00	.598414660e+01
44	.546541680e+05	.968212972e+11	.999999046e+00	.999999878e+03
45	.769228281e+05	.848147497e+11	.988974750e+00	.999999878e+03
46	.512330195e+05	.604394496e+11	.828102052e+00	.667001892e+03
47	.182669199e+05	.681918177e+11	.999999940e+00	.334000977e+03

Table 6.1 (continued)

SYS	OPS COST ($/hr)	INITIAL COST ($)	RELIABILITY (0 to 1)	MASS P/L DELIV (kg/hr)
48	.182660195e+05	.531155763e+11	.667312145e+00	.334000092e+03
49	.188357891e+05	.509999759e+11	.665001571e+00	.333999969e+03
50	.657213281e+05	.391744594e+11	.658923388e+00	.333999298e+03
51	.512831992e+05	.389663089e+11	.535878778e+00	.333988770e+03
52	.551737773e+05	.115011396e+12	.999999940e+00	.999999939e+03
53	.770759375e+05	.853903032e+11	.960498273e+00	.999999695e+03
54	.344580594e+06	.683946598e+11	.908837855e+00	.999999878e+03
55	.171641297e+06	.665346089e+11	.648337185e+00	.999999939e+03
56	.129239195e+06	.661731287e+11	.510040641e+00	.999995850e+03
57	.360973688e+06	.539183391e+11	.931166649e+00	.667000183e+03
58	.157763391e+06	.512172687e+11	.651877642e+00	.666999756e+03
59	.119211594e+06	.508429967e+11	.527073860e+00	.667002197e+03
60	.380230469e+06	.389443584e+11	.947498083e+00	.333999878e+03
61	.146280188e+06	.363195392e+11	.657747567e+00	.333999878e+03
62	.961322422e+05	.356736082e+11	.488609284e+00	.333982391e+03
63	.479462266e+05	.187560899e+11	.236394599e+00	.784326553e+01
64	.572337969e+05	.911536538e+11	.649716496e+00	.100000598e+04
65	.353227695e+05	.859236188e+11	.999999940e+00	.667000244e+03
66	.497968672e+05	.830926029e+11	.999999940e+00	.666999939e+03
67	.674999844e+05	.688912220e+11	.980412066e+00	.666998474e+03
68	.403584766e+05	.701121249e+11	.666527689e+00	.667000061e+03
69	.414935586e+05	.676140974e+11	.662733793e+00	.666998474e+03

Table 6.2

NDSS of Associated "Values" from Linear Value Functions

SYS #	OPERATING COST	INITIAL COST	RELIABILITY	MASS OF OF PAYLOAD DELIVERED
1	.880509675e+00	.256521374e+00	.999902129e+00	.624519944e+00
2	.964257956e+00	.832874596e+00	.998936057e+00	.164293870e-01
3	.946802139e+00	.851405859e+00	.996610343e+00	.142253814e-01
4	.952561319e+00	.832847238e+00	.533011615e+00	.224001775e-02
5	.946191967e+00	.527588010e+00	.999975502e+00	.352494627e+00
6	.808007658e+00	.226148011e-03	.986938357e+00	.100000000e+01
7	.931651175e+00	.777364850e+00	.999997556e+00	.168185323e+00
8	.983620107e+00	.769961298e+00	.999999523e+00	.132339135e+00
9	.972233832e+00	.772168338e+00	.999999642e+00	.129935756e+00
10	.978684962e+00	.789639890e+00	.901215851e+00	.976017956e-02
11	.939812601e+00	.563325882e+00	.999999821e+00	.338609695e+00
12	.948418677e+00	.557542443e+00	.999999344e+00	.334381104e+00
13	.904305995e+00	.351112992e+00	.996550798e+00	.499874830e+00
14	.904299974e+00	.350989699e+00	.996818900e+00	.499872774e+00
15	.904303551e+00	.350923896e+00	.996940553e+00	.499874562e+00
16	.903710186e+00	.349029213e+00	.996483147e+00	.499875873e+00
17	.904300153e+00	.350955307e+00	.996766984e+00	.499874979e+00
18	.904212475e+00	.351245135e+00	.996651947e+00	.499876887e+00
19	.904050887e+00	.351516217e+00	.996765494e+00	.499858677e+00
20	.903486550e+00	.356968760e+00	.996757030e+00	.492875844e+00
21	.903444052e+00	.361319989e+00	.998473763e+00	.490930259e+00
22	.864033639e+00	.246104598e+00	.999913096e+00	.656866431e+00

Table 6.2 (continued)

SYS #	OPERATING COST	INITIAL COST	RELIABILITY	MASS OF OF PAYLOAD DELIVERED
23	.971740663e+00	.645320177e+00	.978301167e+00	.124738261e+00
24	.957487226e+00	.718331456e+00	.999889791e+00	.103403866e+00
25	.988030612e+00	.722798407e+00	.999389350e+00	.700943917e-01
26	.988093078e+00	.722462952e+00	.999389350e+00	.706188008e-01
27	.894236386e+00	.700706005e+00	.999517500e+00	.179944515e+00
28	.925145388e+00	.532944143e+00	.999948084e+00	.374031007e+00
29	.937192857e+00	.533807099e+00	.999976754e+00	.359694064e+00
30	.904017627e+00	.310284615e+00	.100000000e+01	.499874830e+00
31	.952218473e+00	.385256499e+00	.100000000e+01	.250311911e+00
32	.952309191e+00	.431710631e+00	.100000000e+01	.250312120e+00
33	.660877228e+00	.424135447e+00	.907147408e+00	.749436617e+00
34	.952412903e+00	.550886333e+00	.803135395e+00	.250311166e+00
35	.952378154e+00	.551261485e+00	.803070366e+00	.250309557e+00
36	.952380836e+00	.550756395e+00	.803124368e+00	.250311971e+00
37	.952377617e+00	.550777376e+00	.802892148e+00	.250311434e+00
38	.952386558e+00	.551015794e+00	.802072167e+00	.250312120e+00
39	.996311665e+00	.602203429e+00	.969539344e+00	.103233149e-01
40	.996386230e+00	.602209508e+00	.969515681e+00	.102940649e-01
41	.903677821e+00	.278136551e+00	.100000000e+01	.499874830e+00
42	.385629475e+00	.655683339e+00	.957210004e+00	.250312060e+00
43	.910827279e+00	.840747714e+00	.170653790e+00	.448474428e-02
44	.856260419e+00	.158159092e+00	.999999046e+00	.749437511e+00
45	.797694206e+00	.262553483e+00	.988974750e+00	.749437511e+00
46	.865257978e+00	.474491656e+00	.828102052e+00	.499876261e+00

Table 6.2 (continued)

SYS #	OPERATING COST	INITIAL COST	RELIABILITY	MASS OF OF PAYLOAD DELIVERED
47	.951958299e+00	.407086432e+00	.100000000e+01	.250312895e+00
48	.951960623e+00	.538171172e+00	.667312145e+00	.250312209e+00
49	.950462162e+00	.556565881e+00	.665001571e+00	.250312120e+00
50	.827153981e+00	.659386277e+00	.658923447e+00	.250311613e+00
51	.865126014e+00	.661196053e+00	.535878837e+00	.250303745e+00
52	.854893863e+00	.000000000e+00	.100000000e+01	.749437571e+00
53	.797291517e+00	.257549256e+00	.960498273e+00	.749437392e+00
54	.937585905e-01	.405322790e+00	.908837914e+00	.749437511e+00
55	.548586130e+00	.421495497e+00	.648337185e+00	.749437571e+00
56	.660102963e+00	.424638510e+00	.510040700e+00	.749434471e+00
57	.506450236e-01	.531191289e+00	.931166708e+00	.499874979e+00
58	.585084796e+00	.554676592e+00	.651877701e+00	.499874711e+00
59	.686475396e+00	.557930768e+00	.527073860e+00	.499876469e+00
60	.000000000e+00	.661386967e+00	.947498083e+00	.250312060e+00
61	.615285456e+00	.684209228e+00	.657747626e+00	.250312060e+00
62	.747173727e+00	.689825416e+00	.488609284e+00	.250298947e+00
63	.873902142e+00	.836919725e+00	.236394599e+00	.587803777e-02
64	.849475980e+00	.207438067e+00	.649716496e+00	.749442041e+00
65	.907101691e+00	.252912194e+00	.100000000e+01	.499875009e+00
66	.869035006e+00	.277527213e+00	.100000000e+01	.499874830e+00
67	.822476089e+00	.401005298e+00	.980412126e+00	.499873698e+00
68	.893857837e+00	.390389800e+00	.666527748e+00	.499874890e+00
69	.890872598e+00	.412109613e+00	.662733793e+00	.499873698e+00

Table 6.3

NDSS Ranking Based on Figures of Merit for One DM

Top Third		Middle Third		Bottom Third	
Figure of Merit	Sys #	Figure of Merit	Sys #	Figure of Merit	Sys #
.858118594e+00	3	.651489913e+00	61	.561895788e+00	13
.849384725e+00	2	.643730819e+00	51	.561873794e+00	14
.817836702e+00	8	.641863704e+00	35	.561858594e+00	15
.817656755e+00	9	.641648114e+00	34	.561841726e+00	17
.817342460e+00	7	.641560912e+00	36	.560508609e+00	16
.803750217e+00	10	.641525388e+00	37	.551585495e+00	57
.786268115e+00	25	.641504824e+00	38	.537159026e+00	30
.786089540e+00	26	.636705041e+00	62	.528886318e+00	69
.781112671e+00	24	.618957460e+00	60	.517103553e+00	41
.765252054e+00	27	.616272211e+00	49	.516533673e+00	68
.750593960e+00	4	.608297467e+00	32	.512307286e+00	66
.733907580e+00	23	.605491996e+00	48	.505971253e+00	1
.703526616e+00	40	.598767281e+00	46	.502208829e+00	45
.703519464e+00	39	.592924237e+00	47	.501837909e+00	65
.692387283e+00	11	.579368234e+00	31	.498763144e+00	22
.689704537e+00	12	.579171598e+00	67	.498706698e+00	55
.681706667e+00	63	.576393723e+00	58	.493133515e+00	53
.675097167e+00	43	.568370223e+00	33	.486184984e+00	56
.674569130e+00	29	.568158567e+00	21	.484702557e+00	54
.673099220e+00	28	.565450013e+00	59	.446978092e+00	44
.671538889e+00	5	.565181851e+00	20	.404105812e+00	64
.666589916e+00	42	.562158108e+00	19	.350451410e+00	6
.663294911e+00	50	.561987162e+00	18	.348350018e+00	52

Table 6.1

Weightings & NDSS Rankings for Nine Decision Makers

		DECISION MAKERS								
		A	B	C	D	E	F	G	H	I
W E I G H T I N G S	OVERALL COST WEIGHTING	0.5	0.88	0.88	0.17	0.50	0.75	0.14	0.87	0.50
	INITIAL COST WEIGHTING	0.25	0.17	0.50	0.25	0.14	0.83	0.87	0.90	0.83
	OPERATIONAL COST WEIGHTING	0.75	0.83	0.50	0.75	0.86	0.17	0.13	0.10	0.17
	OVERALL PERFORMANCE WEIGHTING	0.50	0.12	0.12	0.83	0.50	0.25	0.86	0.13	0.50
	RELIABILITY WEIGHTING	0.83	0.83	0.83	0.75	0.25	0.83	0.87	0.50	0.83
	MASS OF PAYLOAD DELIVERED WEIGHTING	0.17	0.17	0.17	0.25	0.75	0.17	0.13	0.50	0.17
S		8	8	3	6	6	3	7	3	3
Y		9	26	2	44	44	2	8	2	2
S		2	25	8	52	52	8	9	4	7
T		26	2	9	45	45	9	11	7	8
E		25	9	10	22	53	7	28	10	9
M		3	10	7	1	22	10	12	9	25
		7	3	25	53	1	25	29	8	26
R		24	40	26	30	64	26	45	43	24
A		12	39	24	15	15	24	27	63	27
N		11	24	4	14	14	27	5	25	10
K		5	23	23	17	17	4	2	26	23
I		29	7	27	19	13	23	3	24	11
N		23	12	40	18	18	40	22	27	12
G		28	11	39	13	19	39	44	23	29
		27	5	43	16	16	11	1	62	28
		40	4	63	21	20	12	6	61	5
		39	29	12	41	30	63	24	50	39
		32	32	11	20	21	43	21	51	40
		47	35	5	65	41	29	26	42	42
		31	34	29	66	65	28	25	40	32
		10	36	28	28	33	5	15	39	60
		21	37	35	29	66	42	19	11	47
		15	38	34	5	5	50	14	12	67
		14	28	38	11	[illegible]				

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6	61	5
39	29	12	41	30	63	24	50	39
32	32	11	20	21	43	21	51	40
47	35	5	65	41	29	26	42	42
31	34	29	66	65	28	25	40	32
10	36	28	28	33	5	15	39	60
21	37	35	29	66	42	19	11	47
15	38	34	5	5	50	14	12	67
14	28	38	11	28	61	17	60	21
17	27	36	12	29	51	18	29	20
19	47	37	67	12	35	20	28	19
18	31	49	33	46	34	13	5	18
13	49	51	32	11	36	16	35	15
20	48	48	47	67	37	30	38	14
16	21	50	31	68	38	41	34	17
30	20	32	7	69	62	66	37	13
41	15	47	8	32	60	67	36	16
1	14	31	9	56	49	65	49	31
65	13	62	27	47	32	53	48	33
22	17	46	24	31	48	52	59	35
44	18	21	26	8	46	32	58	34
66	19	20	25	9	47	47	46	36
67	16	19	23	7	31	23	57	37
45	30	18	2	35	67	31	32	38
52	41	13	3	34	58	42	33	30
6	65	14	39	36	33	33	47	46
53	43	15	40	37	21	57	67	57
35	46	17	54	38	59	39	69	45
34	1	16	46	23	20	40	56	41
36	51	69	42	55	19	60	55	1
37	69	67	10	26	18	54	31	4
38	68	30	57	25	13	10	68	66
46	63	61	34	27	14	46	21	22
33	66	68	36	24	15	34	20	65
49	22	41	35	49	17	35	19	50
48	50	65	37	48	16	36	18	53
69	67	66	38	2	57	37	13	61
68	44	1	64	3	30	38	14	44
50	52	59	60	40	69	55	17	54
4	45	22	68	39	41	58	15	49
64	53	33	69	10	68	68	16	48
51	64	45	55	59	66	69	54	58
42	6	58	48	51	1	50	30	51
61	62	53	49	50	45	61	41	62
58	33	44	58	58	65	64	66	69
55	59	42	50	4	22	49	45	6
62	61	64	56	62	55	48	1	68
59	56	56	61	61	53	59	53	55
56	58	55	59	43	56	56	22	52
63	55	52	51	63	51	51	65	59

30	20	32	7	69	62	66	37	13
41	15	47	8	32	60	67	36	16
1	14	31	9	56	43	65	49	31
65	13	62	27	47	[illegible]	53	48	33
22	17	46	24	31	48	52	59	35
44	18	21	26	8	46	32	58	34
66	19	20	25	9	47	47	46	36
67	16	19	23	7	31	23	57	37
45	30	18	2	35	67	31	32	38
52	41	13	3	34	58	42	33	30
6	65	14	39	36	33	33	47	46
53	43	15	40	37	21	57	67	57
35	46	17	54	38	59	39	69	45
34	1	16	46	23	20	40	56	41
36	51	69	42	55	19	60	55	1
37	69	67	10	26	18	54	31	4
38	68	30	57	25	13	10	68	66
46	63	61	34	27	14	46	21	22
33	66	68	36	24	15	34	20	65
49	22	41	35	49	17	35	19	50
48	50	65	37	48	16	36	18	53
69	67	66	38	2	57	37	13	61
68	44	1	64	3	30	38	14	44
50	52	59	60	40	69	55	17	54
4	45	22	68	39	41	58	15	49
64	53	33	69	10	68	68	16	48
51	64	45	55	59	66	69	54	58
42	6	58	48	51	1	50	30	51
61	62	53	49	50	45	61	41	62
58	33	44	58	58	65	64	66	69
55	59	42	50	4	22	49	45	6
62	61	64	56	62	55	48	1	68
59	56	56	61	61	53	59	53	55
56	58	55	59	43	56	56	22	52
63	55	52	51	63	[illegible]	51	65	59
54	42	6	4	54	41	4	64	63
43	54	60	62	42	64	62	44	56
57	57	57	63	57	6	63	6	43
60	60	54	43	60	52	43	52	64

6.3 Sensitivity Development

6.3.1 Development. As illustrated in the last section, each solution in the NDSS is ranked based on the decision maker's predetermined preferences. However, preferences do change, sometimes due to external variables beyond the control of the decision maker. If the analyst has determined how sensitive any particular solution is to changes in the original preferences, he can provide a wealth of information that the decision maker can use. Since a decision maker may be concerned about "selling" his choice of a solution to others (his boss, Congress, etc.), a solution that stays highly ranked over a wide range of preference weightings may be more attractive to the DM than his original top-ranked system. Or several decision makers may be involved in selecting a solution, and a solution that stays in a highly-ranked position over a range of preference weightings may be the best compromise. This section describes one method for accomplishing this sensitivity analysis to determine the robust solutions in the NDSS.

By varying the preference weightings for the objectives at each level of the hierarchy tree, one can determine a solution's robustness and frequency of occurrence within the positions of interest. Ideally, all weightings in the hierarchy would be varied over all values to obtain every possible combination. However, taking every possible combination of weightings is undesirable because of the enormous

number of combinations possible. Keeping the decision maker's value functions constant and changing each preference weighting by 0.1 increments would yield 729 possible combinations for the simple hierarchy tree in Figure 6.1. Fortunately this is not necessary. It is possible to determine where significant changes in the solution ordering occur by examining one hierarchy level at a time. This may indicate the general trend of system ordering throughout all cases.

As an example, the level 3 objective weightings in Figure 6.1 are varied from 0.1 to 0.9 in increments of 0.1. The initial cost and operating cost indices are then multiplied by the DM "values" (Table 6.2) and summed to get a cost "sub-figure of merit" (see Figure 6.3). This sub-figure of merit represents the preference for each solution in the NDSS based on the cost objectives of Level 3. The NDSS may now be rank-ordered for each change in weighting using this cost sub-figure of merit, as shown in Table 6.5. The same procedures are followed for the performance objectives of Level 3 to yield the rankings in Table 6.6. It is now possible to determine which weightings at this level are significant in producing system ordering variations. A discussion of this follows.

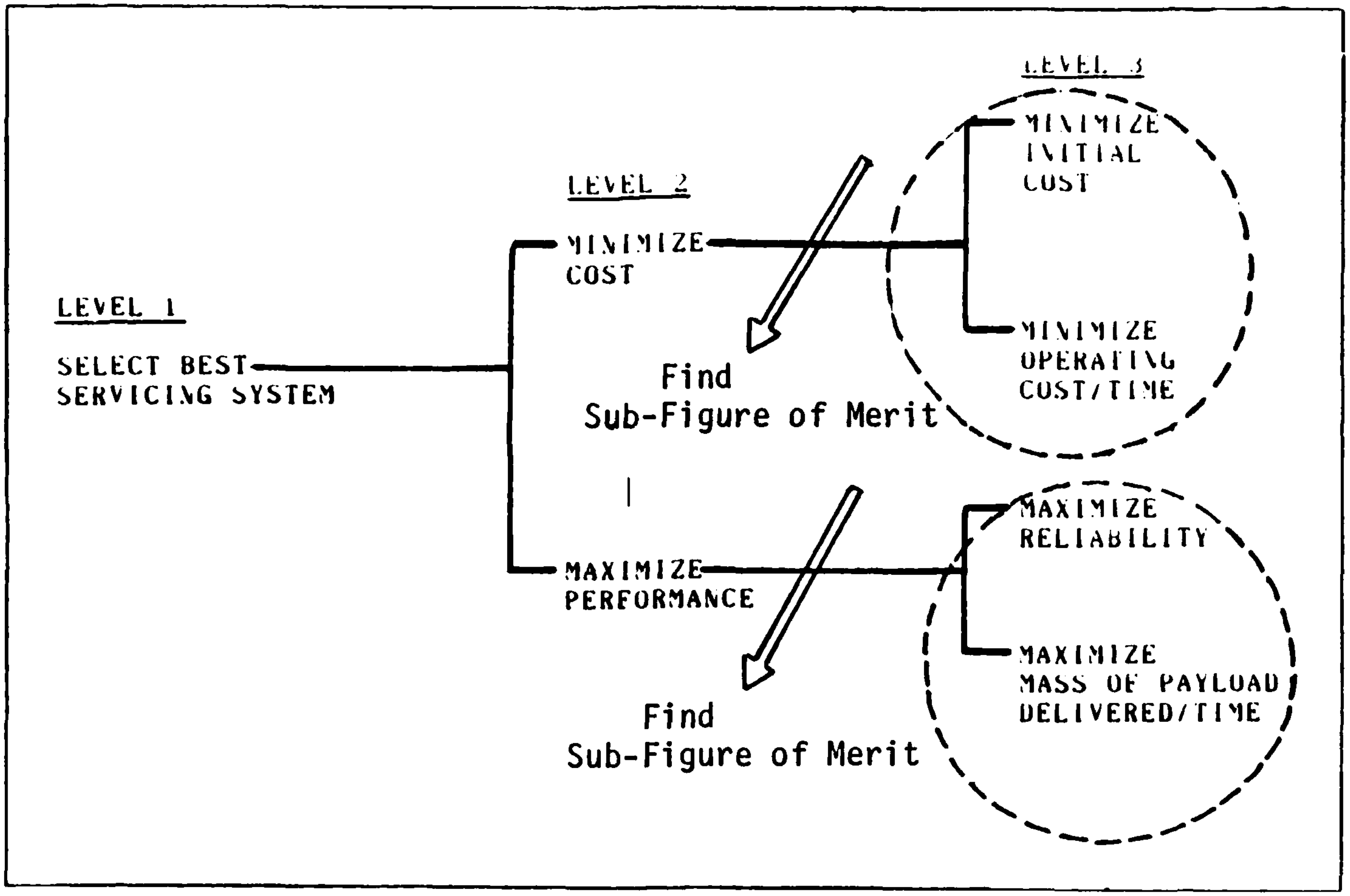

Figure 6.3 Finding the 'Sub-Figure of Merit'

Table 6.5

Cost: Sub-Figure of Merit System Ranking

	Initial Cost Weighting (ICW) (where: Ops Cost Weighting (OPCW)= 1 - ICW)								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
S	8	8	2	2	3	3	3	3	3
Y	26	10	10	3	2	2	2	2	43
S	25	2	8	4	4	4	4	4	2
T	10	25	3	10	10	43	43	43	4
E	40	26	4	8	8	10	63	63	63
M	39	9	9	9	43	8	10	10	10
	9	4	25	43	9	9	8	8	7
R	2	3	26	25	25	63	9	9	9
A	4	40	43	26	63	7	7	7	8
N	23	39	24	7	26	25	25	25	25
K	3	24	7	24	7	26	26	26	26
I	24	23	40	63	24	24	24	24	24
N	7	7	39	23	23	27	27	27	27
G	35	43	23	40	40	23	23	23	62
	34	35	63	39	39	40	51	51	51
	38	38	27	27	27	39	40	62	23
	36	34	49	49	51	51	39	50	61
	37	37	35	12	49	50	50	40	50
	49	36	38	35	12	49	62	39	40
	48	49	34	38	35	11	11	61	39
	12	12	37	34	38	12	12	11	42
	5	48	36	37	34	62	49	12	11
	43	63	12	36	37	35	35	49	12
	11	11	48	11	11	38	38	35	49
	32	5	11	48	36	34	34	38	60
	47	29	5	51	48	37	37	34	35
	29	27	29	5	50	36	36	37	38
	31	32	28	29	5	48	61	36	34
	28	28	51	28	29	29	48	48	37
	27	47	32	50	28	5	29	29	36
	63	31	47	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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	31	32	28	29	5	48	61	36	34
	28	28	51	28	29	29	48	48	37
	27	47	32	50	28	5	29	29	36
	63	31	47	32	62	28	5	28	48
	21	51	31	47	32	61	28	5	29
	13	69	50	31	47	32	59	42	28
	14	21	46	62	46	46	46	59	59
	17	20	69	46	31	47	32	58	5
	15	13	68	69	69	31	42	46	58
	18	14	21	68	61	59	47	32	46
	20	17	20	21	68	69	58	60	32
	19	15	13	20	21	68	69	47	57
	16	18	18	19	20	21	31	69	47
	51	50	14	13	19	20	68	31	69
	30	19	17	18	18	19	67	68	56
	68	68	19	14	13	18	21	67	33
	69	16	15	17	14	13	20	56	67
	65	46	16	15	17	14	19	33	31
	41	30	62	16	15	17	18	21	68
	46	41	30	30	16	15	13	20	55
	1	65	41	67	59	16	14	19	21
	50	1	65	41	67	67	17	18	20
	66	66	67	65	30	58	15	13	19
	22	22	1	61	41	30	16	14	18
	44	67	66	59	65	42	56	17	13
	64	62	22	66	66	41	33	15	14
	67	64	64	1	58	33	30	16	17
	52	44	59	22	1	56	41	55	15
	45	45	44	64	22	65	60	57	16
	53	53	45	45	33	66	55	30	54
	62	52	61	53	56	1	66	41	30
	6	59	53	44	45	22	65	66	41
	59	6	52	58	64	45	1	65	66
	33	61	33	33	53	53	22	1	1
	56	33	56	56	42	55	45	22	65
	61	56	58	52	44	64	53	45	45
	58	58	6	55	55	44	64	53	53
	55	55	55	42	52	60	57	54	22
	42	42	42	6	6	52	44	64	64
	54	54	60	60	60	57	54	44	44
	57	57	57	57	57	6	52	52	52
	60	60	54	54	54	54	6	6	6

Table 6.6

Performance: Sub-Figure of Merit System Ranking

	Reliability Weighting (Rw) (where: Mass P/L Delivered Weighting (MPDw) = 1 - Rw)								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
S	6	6	6	6	6	6	6	6	6
Y	52	52	52	52	52	52	52	52	52
S	44	44	44	44	44	44	44	44	44
T	45	45	45	45	45	45	45	45	22
E	53	53	53	53	53	53	53	22	45
M	54	54	54	54	54	22	22	1	1
	33	33	33	33	22	1	1	53	65
R	64	64	22	22	33	54	54	65	66
A	55	55	1	1	1	33	33	66	41
N	56	22	64	64	65	65	65	41	30
K	22	56	55	55	66	66	66	30	21
I	1	1	56	65	41	41	41	15	15
N	65	65	65	66	30	30	30	14	14
G	66	66	66	41	15	15	15	17	17
	41	41	41	30	14	14	14	19	19
	30	30	30	15	17	17	17	18	18
	15	15	15	14	19	19	19	13	13
	14	14	14	17	18	18	18	16	16
	17	17	17	19	13	13	13	21	20
	18	19	19	18	16	16	16	20	53
	19	18	18	13	20	21	21	67	28
	13	13	13	16	21	20	20	54	29
	16	16	16	20	67	67	67	33	5
	67	67	20	21	57	57	28	28	11
	20	20	67	67	64	28	29	29	12
	57	21	21	57	55	29	5	5	67
	21	57	57	56	28	5	57	11	47
	46	46	46	46	29	11	11	12	32
	68	68	28	28	5	12	12	47	31
	69	69	29	29	11	47	47	32	27
	58	58	68	5	12	32	32	31	7
	59	59	69	11	46	31	31	57	8
	28	28	5	12	56	46	27	27	9

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			[illegible]	28	5	57	11	47
46	46	46	46	29	11	11	12	32
68	68	28	28	5	12	12	47	31
69	69	29	29	11	47	47	32	27
58	58	68	5	12	32	32	31	7
59	59	69	11	46	31	31	57	8
28	28	5	12	56	46	27	27	9
29	29	58	68	47	64	7	7	24
5	5	11	69	32	55	42	8	26
11	11	12	58	31	42	8	9	25
12	12	59	47	42	27	9	24	2
47	47	47	32	60	60	60	42	3
32	32	32	31	27	7	24	26	23
31	31	31	42	7	8	46	25	54
42	42	42	60	68	9	23	60	33
60	60	60	59	69	24	26	23	57
34	34	27	27	58	23	25	2	42
36	36	7	7	8	26	2	3	60
35	35	34	8	9	25	3	39	39
37	37	36	9	24	2	39	40	40
38	38	35	34	23	56	40	46	10
48	27	37	36	26	3	64	10	46
49	7	38	35	25	68	55	34	34
50	48	8	37	34	69	34	36	36
61	49	9	38	36	58	36	35	35
51	50	23	23	35	39	35	37	37
62	61	48	24	37	40	37	38	38
27	51	49	26	38	34	38	64	64
7	8	50	25	59	36	10	55	55
8	9	61	48	2	35	68	68	68
9	62	24	49	3	37	69	69	69
23	23	26	50	39	38	58	58	58
24	24	25	61	40	10	56	48	48
26	26	51	2	48	59	48	49	49
25	25	62	3	49	48	49	50	50
2	2	2	39	10	49	50	61	61
3	3	3	40	50	50	61	56	56
39	39	39	10	61	61	59	59	59
40	40	40	51	51	51	51	51	51
10	10	10	62	62	62	62	62	4
4	4	4	4	4	4	4	4	62
63	63	63	63	63	63	63	63	63
43	43	43	43	43	43	43	43	43

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6.3.2 <u>Analysis of Sub-Figure of Merit Results</u>. From Table 6.5, it is apparent that there is no dramatic change in system ordering as the preference weightings are varied for initial and operational costs. The rankings generally have small, smooth variations across the range of weightings. To simplify the overall sensitivity analysis, certain generalizations may be made from observing some of the characteristics of Table 6.5.

The preference weightings of 0.1 and 0.9 in Table 6.5 can be disregarded in further analysis for two reasons. First, system ordering under these weightings have small variations from weightings of 0.2 and 0.8. Secondly, it is highly unlikely that a military decision maker would prefer minimizing operational cost <u>nine</u> times more than minimizing initial cost and vice versa. Consequently, analysis on initial cost and operational cost weighting values can be limited to 0.2-0.8. Since there are only small variations in the system rankings, and smooth transitions within this range, preference weightings of 0.2, 0.4, 0.6, and 0.8 can be used as representative samples for performing further analysis. This allows the analyst to determine general characteristics of the solution set ranking for different preference weightings, while eliminating the need to run every possibility.

Some of the system rankings in Table 6.6 for the performance sub-figures of merit changed dramatically as

weightings were varied. Most of these changes in the system ordering occurred within the range of 0.3 to 0.9. Also system rankings for the sub-figure of merits for reliability equal to 0.1 and 0.2 have small deviations from the rankings for reliability equal to 0.3. Therefore weightings for reliability of 0.1 and 0.2 are disregarded since they are well represented by the rankings in 0.3 weighting column. Reliability weightings of 0.3, 0.5, 0.7, and 0.9 are then used as representative samples for the range of weightings between 0.3 and 0.9.

The range of weightings identified above for level 3 can be combined with weightings from level 2 to determine the general changes in overall system ordering for any likely case. The Overall Cost Weighting (OCW) and Overall Performance Weighting (OPW) from level 2 are allowed to range from 0.1 to 0.9 in increments of 0.2. All possible combinations of these weightings are combined with the weightings from level 3 to determine an overall figure of merit for each system. This generates 80 different cases of possible system rankings, and the results are shown in Tables 6.7-6.11.

Table 6.7

Overall Weighting Sensitivity Table

Overall Cost Weighting (OCW) = 0.1
Overall Performance Weighting (OPW) = 0.9

Initial Cost Weighting (ICW)
Reliability Weighting (RW)

Operational Cost Weighting (OPCW) = 1 - ICW
Mass P/L Delivered Weighting (MPDW) = 1 - RW

ICW	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
RW	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9
SYSTEM RANKING	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	44
	44	44	45	45	44	44	44	45	44	44	44	45	44	44	44	22
	52	45	44	44	52	45	45	44	52	45	45	44	52	22	22	7
	45	52	53	53	45	52	52	53	45	52	52	52	22	1	1	6
	53	53	52	33	53	53	53	52	22	22	22	22	1	52	45	45
	33	33	33	52	22	22	33	33	53	53	53	53	45	45	28	28
	22	22	54	54	33	33	22	22	1	1	1	1	30	30	29	11
	1	54	22	22	1	1	1	54	30	30	33	33	41	21	11	1
	54	1	1	1	54	54	54	1	41	15	15	54	65	15	52	29
	64	64	55	55	30	15	15	15	65	14	14	15	21	14	12	12
	55	55	64	64	15	14	14	19	15	19	19	14	15	19	5	8
	56	56	56	56	14	17	19	14	14	17	17	19	14	17	21	9
	15	15	15	15	17	19	17	17	17	18	18	17	17	18	30	5
	30	14	14	19	19	18	18	18	19	13	13	18	19	13	15	21
	14	17	19	14	41	13	13	13	18	16	16	13	18	28	14	27
	17	19	17	17	18	30	16	16	13	33	30	16	13	41	19	15
	19	18	18	18	13	16	30	30	16	41	21	21	16	16	17	14
	18	13	13	13	16	41	21	21	21	21	20	30	20	20	18	19
	13	16	16	16	65	65	20	20	20	20	41	20	66	29	13	17
	16	30	30	67	66	21	41	41	66	65	65	41	28	5	20	18
	41	41	41	30	20	20	65	67	33	66	66	66	29	65	16	13
	65	65	20	20	21	66	66	66	67	67	67	65	5	11	7	20
	66	66	21	21	67	67	67	65	28	28	54	67	12	12	41	16
	20	20	67	41	28	28	28	57	29	29	28	28	11	66	8	30
	21	21	65	66	64	29	29	28	5	5	29	29	32	7	9	2
	67	67	66	65	29	64	5	55	11	11	5	5	47	8	65	24
	46	46	46	57	5	5	57	29	12	12	11	11	31	9	66	3
	28	57	57	46	11	11	55	5	54	54	12	12	8	27	27	41
	29	28	28	28	12	12	64	11	32	32	32	57	7	32	24	66
	57	29	29	29	55	55	11	12	47	47	47	7	9	47	2	52
	5	5	5	5	46	46	12	64	31	31	7	27	53	24	26	26
	68	68	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

28	57	57	46	11	11	55	5	54	54	12	12	8	27	27	41
29	28	28	28	12	12	64	11	32	32	32	57	7	32	24	66
57	29	29	29	55	55	11	12	47	47	47	7	9	47	2	52
5	5	5	5	46	46	12	64	31	31	7	27	53	24	26	26
68	68	11	11	57	57	46	46	7	7	31	32	67	31	25	25
69	69	69	58	32	32	32	32	27	27	27	47	27	67	3	65
11	11	68	69	47	47	47	47	8	8	57	31	24	26	32	67
12	12	12	12	31	31	31	56	9	9	8	8	26	25	67	32
58	58	58	68	56	56	56	31	24	57	9	9	25	53	47	47
59	59	59	59	27	7	7	7	26	24	24	24	2	2	31	31
32	32	32	32	7	27	27	27	25	26	26	42	3	3	53	53
47	47	47	47	68	8	42	42	23	25	25	26	23	23	23	23
31	31	31	31	8	9	8	60	57	23	23	25	39	39	39	42
27	42	42	42	69	68	9	8	46	46	42	23	40	40	40	39
7	27	27	60	9	69	68	9	2	2	2	2	33	33	33	40
34	7	7	27	24	42	69	58	3	3	3	3	42	42	42	33
36	34	60	7	42	24	60	68	42	42	46	60	10	54	57	60
35	35	35	35	23	23	24	69	39	39	60	46	54	57	54	57
37	36	34	34	58	58	58	24	40	40	39	39	57	10	60	54
38	37	36	36	26	26	23	23	64	60	40	40	60	60	10	10
42	38	37	37	25	25	26	26	60	64	64	55	46	46	46	46
8	8	38	38	34	60	25	25	10	10	55	10	34	34	34	34
9	9	8	8	36	34	2	2	55	55	10	64	36	36	36	36
23	60	9	9	35	36	34	3	34	34	34	34	35	35	35	35
60	23	23	23	37	35	35	34	36	36	36	35	37	37	37	37
24	24	24	24	38	37	36	35	35	35	35	36	38	38	38	38
48	49	49	50	60	38	37	36	37	37	37	37	64	68	68	55
49	48	50	61	2	2	38	37	38	38	38	38	68	64	69	68
50	50	48	49	3	3	3	38	68	68	68	68	69	69	64	69
26	26	61	48	39	59	59	59	69	69	69	69	48	55	55	58
25	25	26	26	40	39	39	39	58	58	58	58	49	48	48	64
61	61	25	25	59	40	40	40	56	56	56	56	55	49	49	50
51	51	51	51	10	10	10	10	48	48	48	50	50	50	58	48
2	2	2	2	48	48	49	50	49	49	49	48	58	58	50	49
3	3	3	3	49	49	48	61	50	50	50	49	61	61	61	61
62	62	62	62	50	50	50	49	61	61	61	61	56	56	59	59
39	39	39	39	61	61	61	48	59	59	59	59	51	59	56	56
40	40	40	40	51	51	51	51	51	51	51	51	59	51	51	51
10	10	10	10	62	62	62	62	62	62	62	62	4	4	4	4
4	4	4	4	4	4	4	4	4	4	4	4	62	62	62	62
63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63
43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43

Table 6.8

Overall Weighting Sensitivity Table

Overall Cost Weighting (OCW) = 0.3
Overall Performance Weighting (OPW) = 0.7

Initial Cost Weighting (ICW)
Reliability Weighting (RW)

Operational Cost Weighting (OPCW) = 1 - ICW
Mass P/L Delivered Weighting (MPDW) = 1 - RW

ICW	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
RW	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9
SYSTEM RANKING	6	6	6	6	6	6	6	6	6	6	6	7	8	8	2	3
	44	44	45	33	44	44	45	33	44	44	45	8	9	9	8	2
	52	45	33	45	52	45	44	45	52	45	44	9	26	2	3	7
	45	53	53	53	45	53	53	53	22	22	7	45	25	7	9	8
	53	52	44	44	53	52	33	44	45	1	22	11	12	3	7	9
	22	33	22	54	22	22	22	22	1	53	28	3	5	26	25	25
	1	22	52	22	1	1	1	54	53	52	11	28	11	25	26	26
	33	1	1	55	33	33	52	1	15	28	8	12	29	24	24	24
	64	64	55	1	15	15	19	28	14	15	12	2	7	12	27	27
	15	15	64	52	14	14	15	67	17	21	29	29	2	11	11	11
	14	19	54	56	17	19	14	52	19	14	9	27	28	5	12	12
	17	14	56	64	19	17	18	19	18	19	1	5	24	29	29	28
	18	17	19	67	18	18	17	15	13	17	5	33	3	27	5	29
	19	18	15	19	13	13	13	14	16	29	53	6	32	28	28	23
	13	13	18	18	16	16	16	18	21	18	21	24	21	23	23	5
	16	16	14	15	30	21	21	17	30	13	15	22	15	32	32	10
	30	20	17	14	21	20	20	13	20	11	19	53	14	21	39	39
	20	21	13	17	20	30	30	21	41	12	14	26	17	15	40	40
	21	30	16	13	41	41	67	16	65	16	17	25	19	20	21	32
	41	55	21	16	65	65	28	20	5	5	18	44	18	14	20	21
	65	41	20	21	66	66	29	29	28	20	13	1	13	19	47	47
	66	65	67	20	67	67	41	11	29	30	20	21	20	17	15	20
	67	67	30	46	28	28	11	12	12	41	16	19	16	18	19	19
	55	66	41	30	29	29	5	5	11	65	27	15	30	13	14	15
	56	56	65	28	5	5	12	30	66	8	30	14	47	47	17	14
	46	46	66	41	12	11	65	7	67	7	2	18	1	16	18	17
	28	28	46	66	11	12	66	41	8	9	3	17	31	31	13	18
	29	54	28	57	64	46	54	66	32	66	33	13	27	30	16	13
	5	29	29	29	46	7	7	8	9	67	67	20	41	39	31	42
	11	5	5	65	32	64	46	65	7	27	24	16	22	40	30	16
	12	11	11	11	47	8	8	9	47	33	41	67	65	1	10	67
	68	12	12	5	31	9	9	27	31	24	26	30	44	41	1	31
	69	69	69	12	7	32	27	57	33	26	25	23	23	22	22	30
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]								

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												[illegible]	[illegible]	17	14
46	46	66	41	12	11	65	7	67	7	2	18	1	16	18	17
28	28	46	66	11	12	66	41	8	9	3	17	31	31	13	18
29	54	28	57	64	46	54	66	32	66	33	13	27	30	16	13
5	29	29	29	46	7	7	8	9	67	67	20	41	39	31	42
11	5	5	65	32	64	46	65	7	27	24	16	22	40	30	16
12	11	11	11	47	8	8	9	47	33	41	67	65	1	10	67
68	12	12	5	31	9	9	27	31	24	26	30	44	41	1	31
69	69	69	12	7	32	27	57	33	26	25	23	23	22	22	30
54	68	68	58	8	27	55	46	26	25	52	41	66	65	67	1
32	32	58	69	9	47	24	55	25	2	65	66	52	44	41	22
47	58	7	7	27	31	32	24	24	32	66	65	40	66	65	45
31	7	57	68	24	54	64	3	27	3	23	54	39	45	66	41
7	47	59	59	23	24	47	2	23	47	32	32	6	67	45	66
8	31	27	27	26	26	26	26	2	31	47	42	45	10	44	65
58	59	8	8	25	25	25	25	3	23	31	52	67	6	53	60
27	8	9	9	68	55	31	42	40	39	39	47	53	52	6	44
59	27	32	42	55	23	2	23	39	40	40	31	10	53	52	53
9	9	47	32	69	2	3	32	46	46	10	10	33	33	42	33
34	35	31	24	2	3	23	47	10	10	46	57	46	46	33	57
35	34	24	47	3	69	57	64	34	35	54	39	34	42	46	6
36	36	35	31	34	68	56	31	35	34	42	40	36	34	35	52
37	37	34	35	35	56	69	56	36	36	57	46	35	35	34	54
38	38	36	34	36	35	42	60	37	37	35	60	37	36	36	46
23	24	37	36	37	34	68	58	38	38	34	35	38	37	37	35
24	23	38	37	38	36	35	10	64	42	36	34	42	38	38	34
26	57	23	38	54	37	34	69	68	54	37	36	48	57	60	36
25	26	26	60	56	38	36	35	69	64	38	37	49	60	57	37
49	25	25	23	39	39	37	34	42	69	60	38	68	54	54	38
48	49	42	3	40	40	38	36	54	68	55	55	69	49	49	50
2	48	2	26	10	10	10	37	48	57	64	58	64	48	50	61
50	2	3	25	48	58	58	38	49	55	69	50	54	68	48	49
3	50	50	2	49	57	39	68	55	49	68	69	50	69	69	48
57	3	49	50	58	42	40	39	50	48	58	68	57	50	68	58
39	42	48	61	59	49	59	40	57	50	50	64	60	64	61	69
40	51	51	49	50	48	60	59	58	58	49	61	61	61	58	68
51	10	61	48	42	59	50	50	56	60	48	49	58	58	55	55
10	39	10	51	57	50	49	61	61	56	61	48	55	55	64	4
42	40	60	10	51	61	48	49	51	61	56	56	4	4	4	51
61	61	62	62	61	51	61	48	59	59	59	59	51	51	51	64
62	62	39	39	62	60	51	51	60	51	51	51	59	59	59	59
4	60	40	40	4	62	62	62	4	4	4	4	56	56	62	62
60	4	4	4	60	4	4	4	62	62	62	62	62	62	56	56
63	63	63	63	63	63	63	63	63	63	63	63	63	63	63	63
43	43	43	43	43	43	43	43	43	43	43	43	43	43	43	43

Table 6.9

Overall Weighting Sensitivity Table

Overall Cost Weighting (OCW) = 0.5
Overall Performance Weighting (OPW) = 0.5

Initial Cost Weighting (ICW)
Reliability Weighting (RW)

Operational Cost Weighting (OPCW) = 1 - ICW
Mass P/L Delivered Weighting (MPDW) = 1 - RW

ICW	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
RW	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9
SYSTEM RANKING	6	6	6	33	6	6	7	7	8	8	8	3	8	2	3	3
	44	45	33	7	44	8	8	8	9	9	3	2	9	8	2	2
	45	44	45	8	22	12	9	9	12	7	9	7	26	3	8	8
	52	53	53	9	1	11	3	3	5	2	2	8	25	9	9	9
	53	22	44	45	45	9	2	2	11	3	7	9	2	25	7	7
	22	1	7	3	52	29	11	27	29	26	25	24	3	26	25	25
	1	33	22	53	53	28	12	24	28	25	26	25	24	7	26	26
	15	52	28	11	15	5	28	26	26	24	24	26	7	24	24	24
	14	19	11	28	14	7	29	25	25	12	27	27	12	27	27	27
	17	15	8	2	17	45	5	11	7	11	11	10	23	23	10	10
	13	18	12	12	18	44	27	12	1	5	12	11	11	12	23	23
	18	14	29	29	13	22	24	33	2	29	29	12	5	11	11	11
	19	13	1	55	19	1	26	28	44	28	28	23	29	10	12	12
	16	17	9	27	16	53	25	29	15	27	5	28	40	5	40	39
	64	16	5	5	21	15	33	5	14	23	10	29	39	40	39	40
	20	28	46	6	20	19	45	10	17	10	23	5	28	39	29	29
	21	21	19	46	5	14	53	23	18	21	40	39	32	29	5	28
	30	20	21	56	12	21	23	45	19	15	39	40	27	28	28	5
	41	29	18	54	29	18	21	67	21	19	21	42	47	32	32	42
	65	11	14	24	30	17	22	53	13	14	20	33	31	47	47	32
	33	12	15	22	11	13	19	46	24	17	19	67	10	31	31	47
	5	5	13	67	28	16	10	21	16	18	15	21	21	21	21	31
	28	30	17	26	41	20	18	20	20	13	18	20	15	20	20	67
	29	64	16	25	65	2	15	19	22	20	14	32	14	15	19	21
	12	46	20	44	8	26	14	18	6	16	17	19	17	19	15	20
	11	41	67	1	66	25	17	15	30	40	13	18	19	14	14	19
	66	67	27	21	9	30	13	14	3	39	16	15	18	17	18	15
	46	65	3	19	7	3	20	13	23	32	32	14	20	18	17	18
	67	8	30	18	67	24	16	17	41	1	67	17	13	13	13	14
	69	7	2	13	32	27	1	16	65	30	47	13	16	16	16	17
	68	9	56	14	26	41	6	42	32	22	30	16	30	30	67	13
	8	66	55	15	25	65	44	22	47	47	45	47	41	41	30	60
	32	69	24	17	47	33	67	1	31	41	1	45	65	65	41	16
	9	56	64	20	31	67	30	30	27	44	22	46	1	1	1	35
	7	27	41	16	24	23	46	44	52	45	31	30	22	67	65	34
	47	68	26	58	23	52	41	54	45	31	33	31	66	22	66	30
	31	24	25	10	46	66	32	39	66	65	41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	1	66	25	17	15	30	40	13	18	19	14	14	19
[illegible]	[illegible]	[illegible]	21	9	30	13	14	3	39	16	15	18	17	18	15
[illegible]	[illegible]	[illegible]	19	7	3	20	13	23	32	12	14	20	18	17	18
[illegible]	[illegible]	[illegible]	18	67	24	16	17	41	1	67	17	13	13	13	14
[illegible]	[illegible]	2	13	32	27	1	16	65	30	47	13	16	16	16	17
68	[illegible]	[illegible]	14	26	41	6	42	32	22	30	16	30	30	67	13
8	[illegible]	55	15	25	65	44	22	47	47	45	47	41	41	30	60
32	[illegible]	[illegible]	17	47	33	67	1	31	41	1	45	65	65	41	16
9	[illegible]	[illegible]	20	31	67	30	30	27	44	22	46	1	1	1	35
7	27	41	16	24	23	46	44	52	45	31	30	22	67	65	34
47	68	26	58	23	52	41	54	45	31	33	31	66	22	66	30
31	24	35	10	46	66	32	39	66	65	41	35	44	66	35	36
56	26	[illegible]	59	2	46	65	40	40	67	53	1	67	44	34	37
35	25	65	23	27	32	66	32	39	66	65	34	52	45	36	38
34	2	56	30	33	47	47	35	53	53	66	36	45	35	37	33
36	23	23	50	3	10	40	34	10	6	44	37	6	34	22	41
37	32	69	57	64	31	39	36	67	46	46	38	53	36	38	46
38	3	10	42	40	40	35	37	46	52	35	60	34	37	45	66
23	55	68	69	39	39	34	38	35	35	34	22	35	38	42	1
26	47	35	64	35	35	36	6	34	34	36	53	36	53	46	4
25	35	34	41	34	34	37	41	36	36	37	41	37	46	53	22
24	34	36	35	36	36	38	57	37	37	38	66	38	52	44	45
27	36	37	34	37	37	31	50	38	38	6	57	46	6	33	65
2	37	38	36	38	38	52	55	33	33	42	65	33	33	4	57
49	38	59	37	10	64	69	66	49	49	52	4	49	49	50	50
48	31	32	38	69	69	50	47	48	48	50	50	48	48	49	53
55	10	58	66	68	68	68	58	68	69	49	44	68	4	48	61
3	49	47	61	49	49	49	65	69	68	4	61	69	42	52	44
10	48	50	68	48	48	55	60	64	50	48	54	50	50	6	49
40	59	49	51	50	50	64	61	50	4	69	49	4	69	60	48
39	40	31	65	56	55	48	4	4	64	68	58	64	68	61	54
59	39	48	62	55	56	42	31	51	42	51	48	51	51	51	51
50	50	51	4	51	51	56	56	55	51	61	6	42	61	69	58
51	51	54	32	4	4	4	59	56	58	58	51	61	64	68	62
58	58	40	49	59	58	58	51	58	61	55	55	58	58	57	69
4	4	39	48	58	59	51	49	42	55	64	69	62	62	58	6
62	62	4	52	62	42	59	69	59	59	54	62	59	59	62	52
61	54	62	47	61	61	61	48	61	56	57	68	55	55	54	68
54	61	61	60	42	62	54	68	62	62	60	59	56	60	59	59
43	42	42	39	63	54	62	62	63	54	62	52	63	57	55	55
63	43	57	40	54	63	57	52	43	57	59	56	43	54	64	63
42	63	63	31	43	43	60	64	54	63	56	64	54	56	63	43
57	57	43	63	57	57	63	63	57	43	63	63	57	63	56	56
60	60	60	43	60	60	43	43	60	60	43	43	60	43	43	64

Table 6.10

Overall Weighting Sensitivity Table

Overall Cost Weighting (OCW) = 0.7
Overall Performance Weighting (OPW) = 0.3

Initial Cost Weighting (ICW)
Reliability Weighting (RW)

Operational Cost Weighting (OPCW) = 1 - ICW
Mass P/L Delivered Weighting (MPDW) = 1 - RW

ICW	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
RW	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9
SYSTEM RANKING	8	8	8	3	8	8	3	3	8	8	3	3	8	2	3	3
	9	9	3	2	9	9	2	2	9	2	2	2	2	3	2	2
	12	7	9	7	26	2	8	7	26	3	8	7	9	8	8	8
	5	2	2	8	25	3	9	8	25	9	9	8	26	9	9	9
	11	3	7	9	12	7	7	9	2	7	7	9	25	25	7	7
	29	26	10	10	2	26	10	10	3	25	25	10	3	26	25	10
	28	25	25	4	5	25	25	25	24	26	26	25	24	7	26	25
	26	10	26	24	11	10	26	26	7	24	10	26	7	24	10	26
	25	24	24	25	7	24	24	24	23	10	24	24	40	10	24	24
	7	12	27	26	29	12	27	27	12	23	27	27	39	23	27	27
	6	11	4	27	24	23	23	4	10	27	23	23	23	40	23	23
	15	5	11	43	3	11	11	23	40	12	11	4	10	39	40	4
	14	29	12	63	23	27	12	11	39	11	12	11	12	27	39	40
	13	28	23	23	28	5	4	12	11	40	40	12	11	12	11	39
	17	23	29	11	10	29	29	29	5	39	39	40	5	11	12	11
	18	27	28	12	40	28	5	28	29	5	29	39	29	5	29	12
	19	4	5	50	39	40	28	5	28	29	4	29	27	29	5	29
	1	35	43	28	32	39	40	63	32	28	5	28	28	28	28	28
	2	34	35	29	15	4	39	43	27	32	28	5	32	32	4	5
	16	36	34	51	14	35	35	40	47	47	35	50	47	47	32	42
	21	37	38	5	17	34	34	39	31	35	34	42	31	31	35	50
	20	38	36	62	13	36	36	50	21	34	36	63	21	35	34	35
	44	40	37	61	18	37	37	51	15	4	37	43	20	34	36	34
	23	39	40	33	19	38	38	61	14	36	38	35	15	36	37	36
	24	46	39	35	21	32	50	42	17	37	32	34	14	37	38	37
	22	21	46	34	16	21	46	62	13	38	47	36	17	38	47	38
	30	19	51	38	20	20	51	35	18	31	50	37	13	4	31	63
	3	18	50	36	47	19	49	34	19	21	49	38	18	21	50	61
	10	13	63	37	27	18	32	36	20	20	31	61	19	20	21	32
	41	14	49	46	31	15	43	38	16	19	46	51	16	19	49	43
	65	15	48	40	30	14	63	37	30	15	21	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

3	18	50	36	47	19	49	34	19	21	49	38	18	21	50	61
10	13	63	37	27	18	32	36	20	20	31	61	19	20	21	32
41	14	49	46	31	15	43	38	16	19	46	51	16	19	49	43
65	15	48	40	30	14	63	37	30	15	21	62	35	15	20	51
32	17	33	39	1	13	48	46	35	18	20	32	34	14	19	47
35	20	21	59	41	17	21	49	34	14	48	49	36	18	18	60
34	16	20	42	35	16	20	33	36	13	19	46	37	17	15	49
36	49	62	49	34	47	19	48	37	17	51	48	30	13	14	62
37	32	19	58	36	46	18	58	38	16	18	47	38	16	13	31
38	48	18	48	37	31	13	32	41	30	14	60	41	30	17	46
47	1	13	56	65	49	14	59	65	49	15	67	65	41	16	48
40	30	14	67	38	30	15	67	1	46	13	33	1	49	48	67
39	22	15	55	22	48	17	21	22	48	17	21	66	48	46	21
46	47	17	21	44	1	47	60	66	41	16	31	22	67	67	20
45	45	16	69	6	41	16	20	44	67	67	20	49	65	51	19
31	69	67	20	66	22	67	47	49	1	63	19	67	46	30	18
27	41	32	19	46	67	31	19	48	65	43	18	48	1	63	14
53	44	69	18	49	65	33	18	46	22	30	13	44	66	41	13
52	67	47	13	48	45	62	13	67	66	41	14	4	22	43	15
49	53	45	14	45	50	30	14	4	50	62	15	46	50	42	17
69	31	68	17	52	66	1	15	45	45	33	17	45	51	65	16
48	68	59	15	53	51	69	17	52	51	1	16	52	45	66	33
64	51	30	32	67	44	61	16	53	44	61	58	53	44	61	30
66	65	1	16	69	69	41	31	6	53	65	59	69	53	1	58
68	50	53	68	4	53	45	69	69	69	66	30	68	69	62	57
67	6	22	60	68	68	22	30	68	68	22	57	6	68	22	41
4	66	61	45	64	33	68	55	50	33	45	69	50	63	33	59
51	33	31	47	51	43	53	45	51	43	42	41	51	43	45	66
33	43	56	53	50	63	65	57	64	63	69	45	64	33	69	1
50	64	41	30	33	6	66	56	33	6	53	1	33	52	53	65
43	63	58	57	43	64	59	68	43	52	68	66	43	62	68	69
56	52	65	31	63	52	58	53	63	62	44	68	63	6	44	22
63	62	66	1	62	62	44	1	62	64	59	22	62	61	58	45
59	56	44	22	56	59	42	22	59	61	58	53	61	64	59	68
62	59	55	54	59	61	56	41	56	59	56	65	59	42	60	53
55	58	64	41	58	56	55	66	61	58	55	55	58	59	52	55
58	55	6	66	61	58	64	65	58	56	64	56	56	58	55	54
61	61	42	65	55	55	6	54	55	42	6	54	42	56	56	44
42	42	52	44	42	42	52	44	42	55	52	44	55	55	64	56
54	54	54	64	54	54	60	64	54	54	60	64	54	60	6	64
57	57	57	6	57	57	57	6	57	57	57	6	57	57	57	52
60	60	60	52	60	60	54	52	60	60	54	52	60	54	54	6

Table 6.11

Overall Weighting Sensitivity Table

Overall Cost Weighting (OCW) = 0.9
Overall Performance Weighting (OPW) = 0.1

Initial Cost Weighting (ICW)
Reliability Weighting (RW)

Operational Cost Weighting (OPCW) = 1 - ICW
Mass P/L Delivered Weighting (MPDW) = 1 - RW

ICW	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8	0.2	0.4	0.6	0.8
RW	0.3	0.3	0.3	0.3	0.5	0.5	0.5	0.5	0.7	0.7	0.7	0.7	0.9	0.9	0.9	0.9
SYSTEM RANKING	8	2	3	3	8	2	3	3	8	2	3	3	8	2	3	3
	9	3	2	2	9	3	2	2	2	3	2	2	2	3	2	2
	26	8	8	4	26	8	8	4	26	8	8	4	25	8	8	10
	25	9	4	43	25	9	10	10	25	9	10	10	26	9	10	8
	2	10	10	10	2	10	9	8	9	10	9	8	9	10	9	9
	10	4	9	8	10	25	4	9	10	25	7	9	10	25	7	4
	3	25	7	9	3	26	7	7	3	26	4	7	3	26	4	7
	24	26	43	7	40	7	25	43	40	7	25	43	40	7	25	25
	40	7	25	63	39	4	26	63	39	4	26	63	39	24	26	26
	39	24	26	25	24	24	43	25	24	24	24	25	24	4	24	43
	23	43	63	26	23	23	24	26	23	23	43	26	23	23	43	63
	7	23	24	24	7	40	63	24	7	40	63	24	7	40	27	24
	4	40	27	27	4	39	27	27	4	39	27	27	4	39	63	27
	12	39	23	23	12	43	23	23	12	27	23	23	12	27	23	23
	11	63	40	51	11	27	40	51	11	43	40	40	11	43	40	40
	5	27	39	62	5	63	39	50	5	12	39	39	5	12	39	39
	35	12	51	50	29	12	11	62	29	11	11	50	29	11	11	50
	34	11	11	40	35	11	12	40	35	63	12	51	27	63	12	51
	38	5	12	39	34	5	51	39	34	5	51	62	35	5	29	62
	36	35	50	61	36	29	50	61	36	29	50	61	34	29	51	11
	37	38	35	11	38	35	29	11	37	35	29	11	36	35	5	12
	29	34	38	12	37	34	36	12	38	34	5	12	37	34	50	61
	49	36	34	35	28	38	5	29	27	38	35	29	38	38	35	29
	48	37	37	38	49	36	38	35	28	36	34	35	32	36	34	28
	28	29	36	34	27	37	34	38	32	37	38	38	28	37	38	5
	43	49	29	37	48	36	34	49	28	36	34	47	28	36	35	35
	27	28	5	36	32	49	37	37	48	49	37	36	31	49	37	34
	32	48	49	49	47	48	28	36	47	48	28	37	49	48	28	38
	47	51	28	29	31	51	49	28	31	51	49	28	48	32	49	36
	31	50	62	28	43	32	48	5	43	32	48	5	43	51	48	37
	63	32	48	5	63	50	62	49	21	47	62	49	21	47	62	49
	21	47	61	48	21	47	32	48	20	50	32	42	20	50	32	42
	13	31	46	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

28	29	36	34	27	37	34	38	32	37	38	38	28	37	38	5
43	49	29	37	48	36	34	49	28	36	34	47	28	36	35	35
27	28	5	36	32	49	37	37	48	49	37	36	31	49	37	34
32	48	49	49	47	48	28	36	47	48	28	37	49	48	28	38
47	51	28	29	31	51	49	28	31	51	49	28	48	32	49	36
31	50	62	28	43	32	48	5	43	32	48	5	43	51	48	37
63	32	48	5	63	50	62	49	21	47	62	49	21	47	62	49
21	47	61	48	21	47	32	48	20	50	32	42	20	50	32	42
13	31	46	42	20	31	61	42	13	31	61	48	13	31	47	48
14	46	32	59	13	46	46	59	14	46	46	59	15	46	61	59
20	69	47	58	14	21	47	46	15	21	47	46	14	21	46	46
15	62	59	46	15	20	31	58	17	20	31	58	17	20	31	32
17	21	31	32	17	19	69	32	18	19	21	32	18	19	21	58
18	20	69	60	18	18	59	60	19	18	69	60	19	18	20	60
19	19	68	47	19	13	21	47	16	13	20	47	16	13	19	47
16	18	21	69	16	14	20	69	63	14	59	31	30	14	18	31
51	13	20	33	30	17	68	31	30	15	19	67	63	15	13	67
30	14	19	67	51	15	19	67	51	17	18	69	41	17	14	69
69	17	18	68	41	62	18	33	41	16	13	33	65	16	17	21
68	15	13	31	46	16	13	68	65	62	14	21	51	62	15	20
46	16	14	56	69	69	14	21	46	69	17	20	46	30	16	33
41	68	17	21	65	68	17	20	69	68	15	68	69	69	69	19
65	30	15	20	68	30	15	19	68	30	16	19	68	68	67	18
1	41	16	19	1	41	16	18	1	41	67	18	1	41	59	13
50	67	67	18	50	67	67	13	50	67	68	13	50	67	68	14
22	65	58	13	66	65	30	14	66	65	30	14	66	65	30	17
66	1	30	14	22	1	58	17	22	1	58	17	22	66	42	15
67	66	33	17	67	66	42	15	67	66	42	15	67	1	58	16
44	22	41	15	44	22	41	16	44	22	41	16	44	22	41	68
64	59	42	16	64	61	33	56	64	61	33	56	45	61	65	30
45	61	56	55	45	59	65	55	45	59	65	57	64	59	66	57
53	45	1	57	53	45	66	57	53	45	66	30	53	45	33	56
52	64	65	30	52	53	1	30	52	53	1	55	52	53	1	55
62	53	66	41	62	44	56	41	62	44	22	41	62	44	22	41
6	44	22	66	6	64	22	66	6	64	56	66	6	64	45	66
59	33	45	1	59	33	45	1	59	33	45	1	59	33	56	65
33	56	53	45	33	58	53	65	33	58	53	65	33	58	53	1
56	58	55	65	56	56	55	45	61	56	55	45	61	56	44	22
61	52	64	53	61	52	64	22	56	52	44	22	56	52	55	45
58	6	44	22	58	6	44	53	58	6	64	53	58	6	64	53
55	55	60	54	55	55	60	54	55	42	60	54	55	42	60	54
42	42	6	64	42	42	52	64	42	55	52	64	42	55	52	64
54	60	52	44	54	60	6	44	54	60	6	44	54	60	57	44
57	57	57	6	57	57	57	6	57	57	57	52	57	57	6	52
60	54	54	52	60	54	54	52	60	54	54	6	60	54	54	6

Table 6.12

Systems Found In Number One Position

System #	#Times in 1st Position	% Time in 1st Position
6	31	38.75
3	19	23.75
8	18	22.50
2	7	8.75
7	3	3.75
33	1	1.25
44	1	1.25
Note-Values taken from total of 80 runs with varied weightings.		

6.3.3 Analysis of Overall Figure of Merit Results. Table 6.12 presents a summary of the systems that appear in the "top-ranked" position for the range of preference weightings described above. A complete listing of the system orderings may be found in Tables 6.7-6.11 for the weightings used.

Seven out of the sixty-nine different candidates in the NDSS (systems 2, 3, 6, 7, 8, 33, and 44) appear in the number one ranked position for the weightings used. Each of these systems represents a unique combination of decision maker preferences. Systems which appear in the top-ranked position with a frequency of 5 percent or more are shown in Figures 6.4 to 6.7.

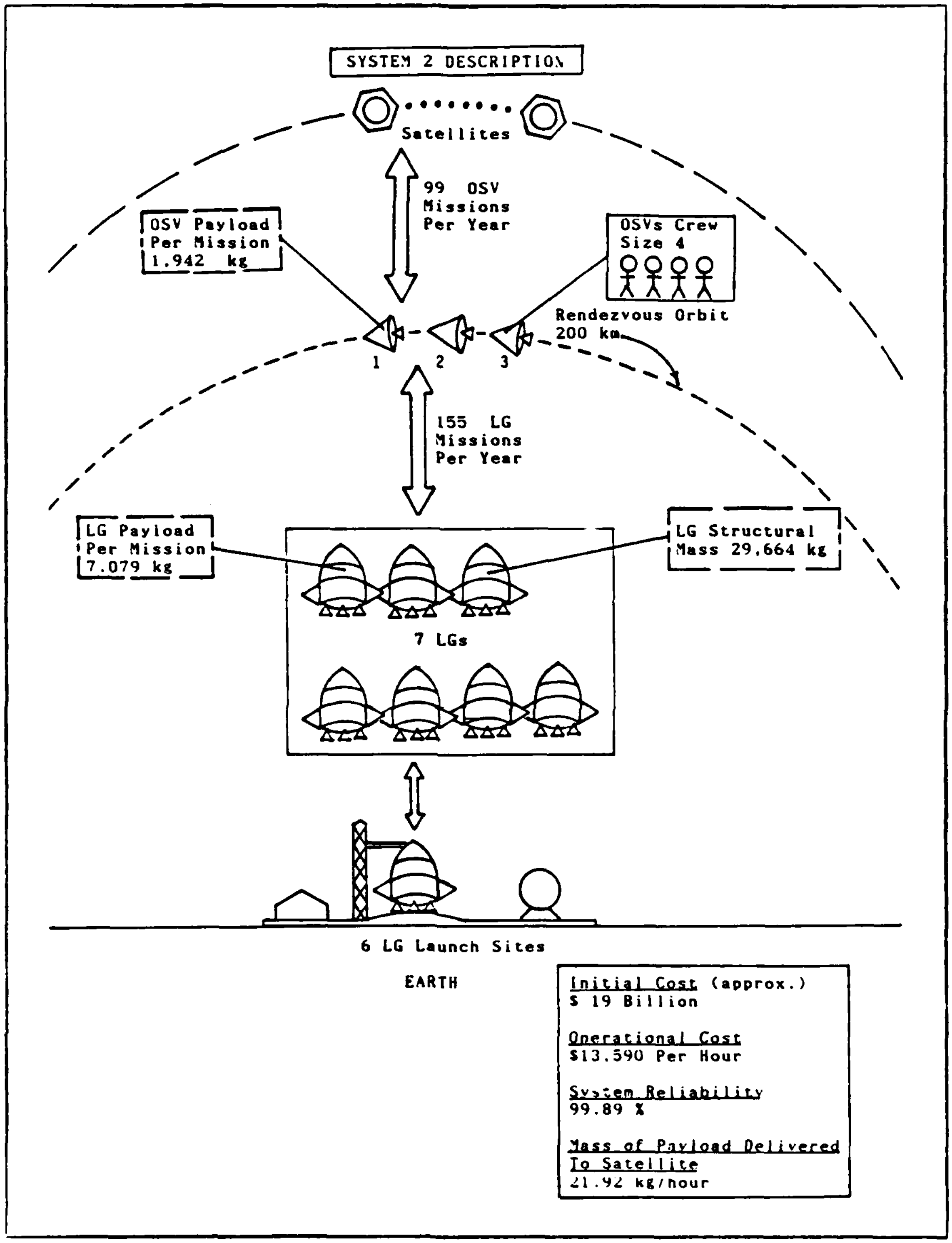

Figure 6.4 Physical Description of System 2

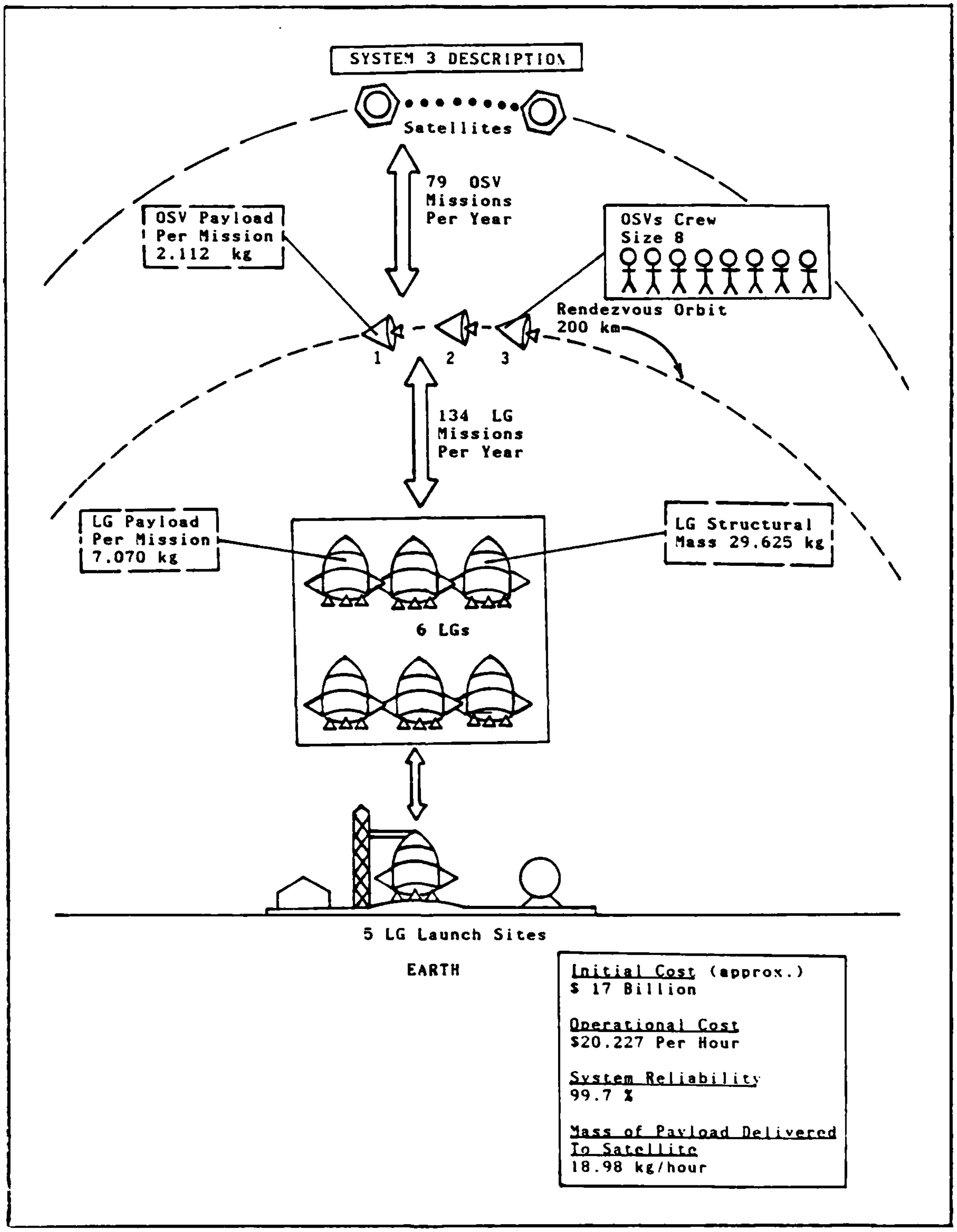

Figure 6.5 Physical Description of System 3

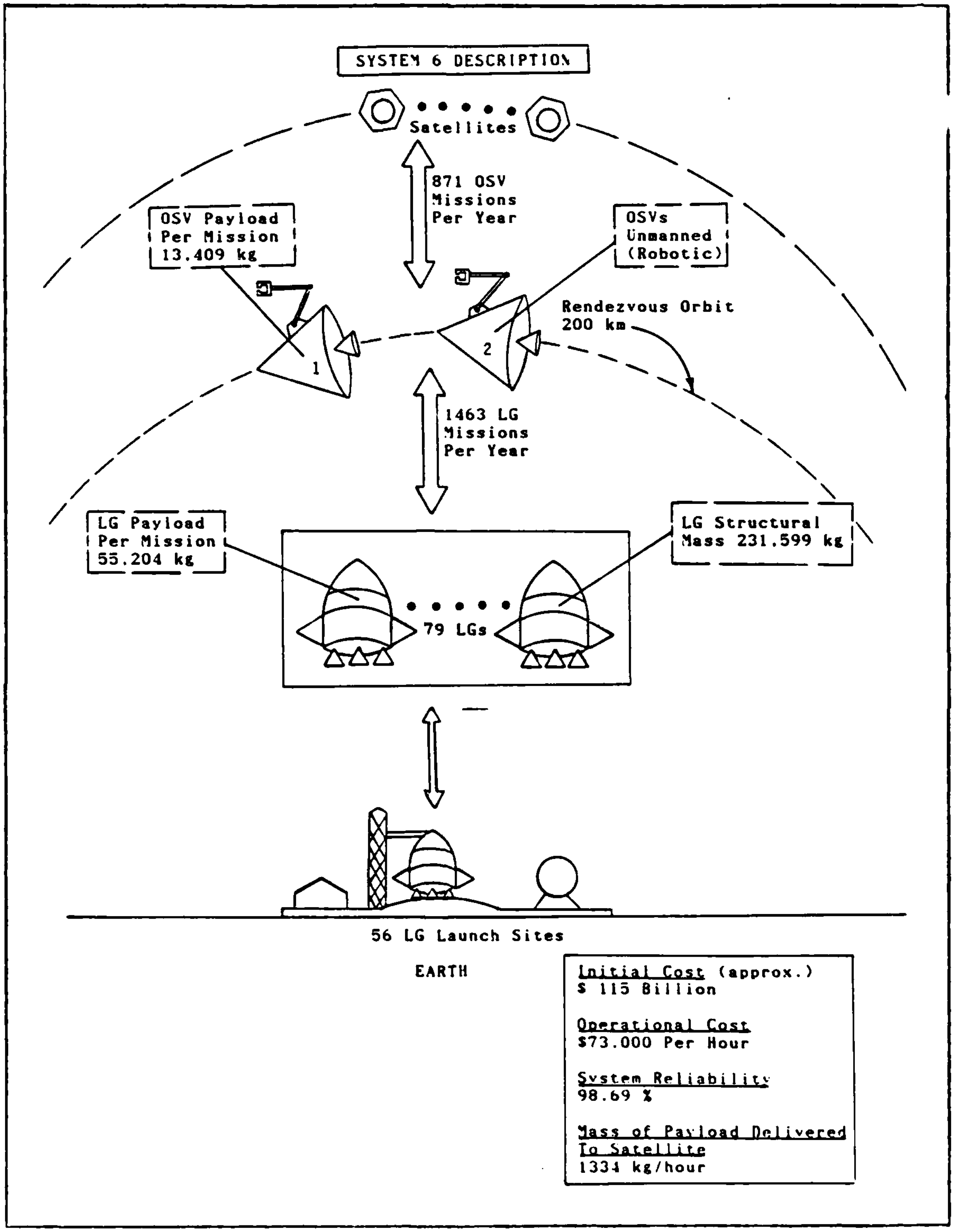

Figure 6.6 Physical Description of System 6

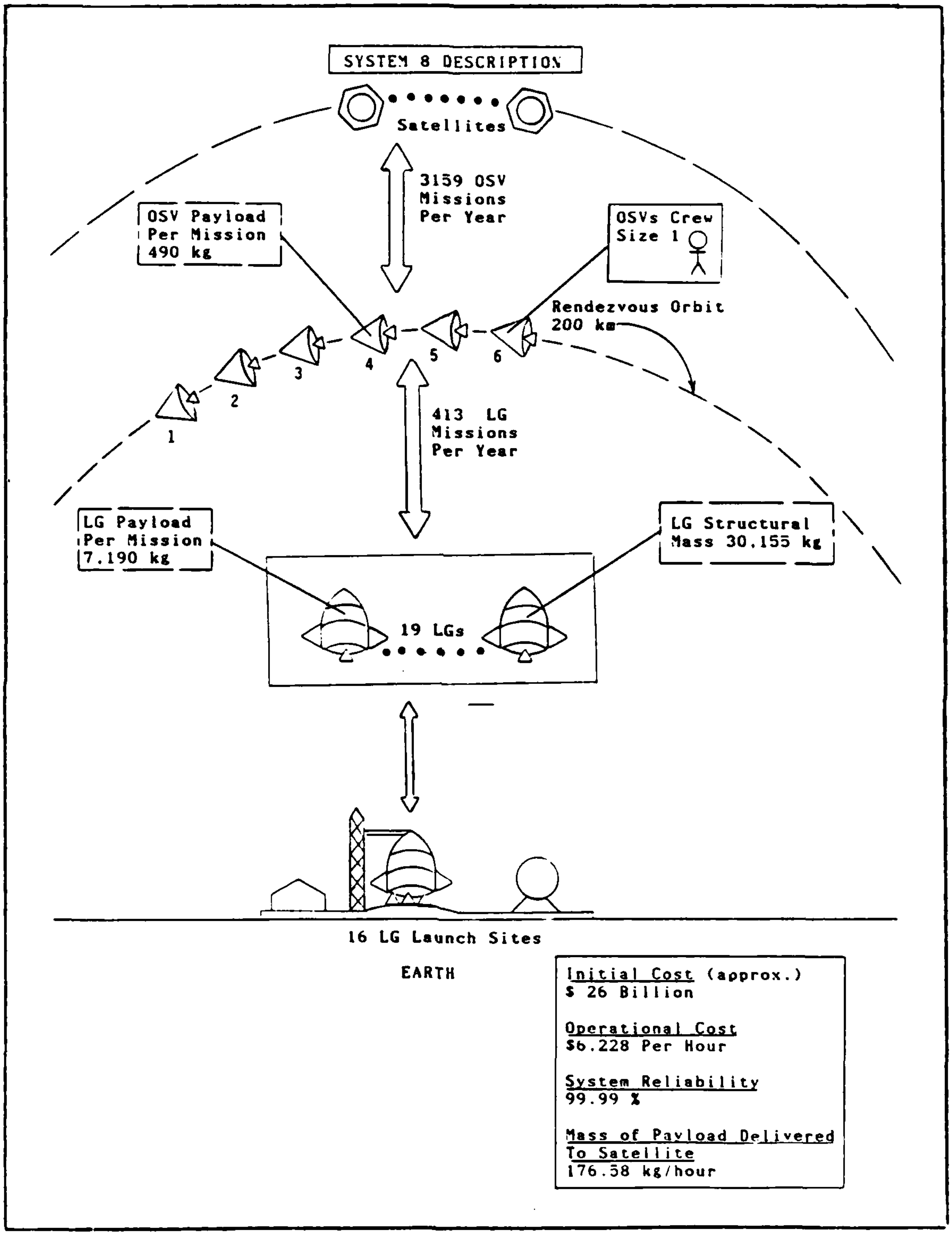

Figure 6.7 Physical Description of System 8

To demonstrate the weightings that permit each of the solutions to appear in the number one position, a plot of the level 3 objectives for constant values of the level 2 objectives is shown in Figure 6.8. Since the hierarchy tree used has only three independent objectives, it is possible to hold one of the objective weightings constant, and look at a plane generated by the other two objective weightings. In this way a decision maker or analyst can visualize what conditions permit a particular system to achieve the top ranking.

For example, suppose an analyst has determined a decision maker's values, and wishes to determine how robust the top-ranked system is. Assume the decision maker's values produce weights corresponding to an overall performance weighting of 0.9, reliability weighting of 0.5, and an initial cost weighting of 0.2. These values indicate that the decision maker desires a system with high performance qualities, moderate reliability, and a system which greatly minimizes operational cost. Referring to Figure 6.8, one can see that system 6 is the top-ranked system for these conditions. In addition, the decision makers preference weightings can change over a wide range, and system 6 still remains ranked above the other systems. System 6 remains in the "top" position because its performance measures for mass of payload delivered and reliability are larger, when combined, than any other member of the NDSS. A physical realization for system 6 is shown in Figure 6.6.

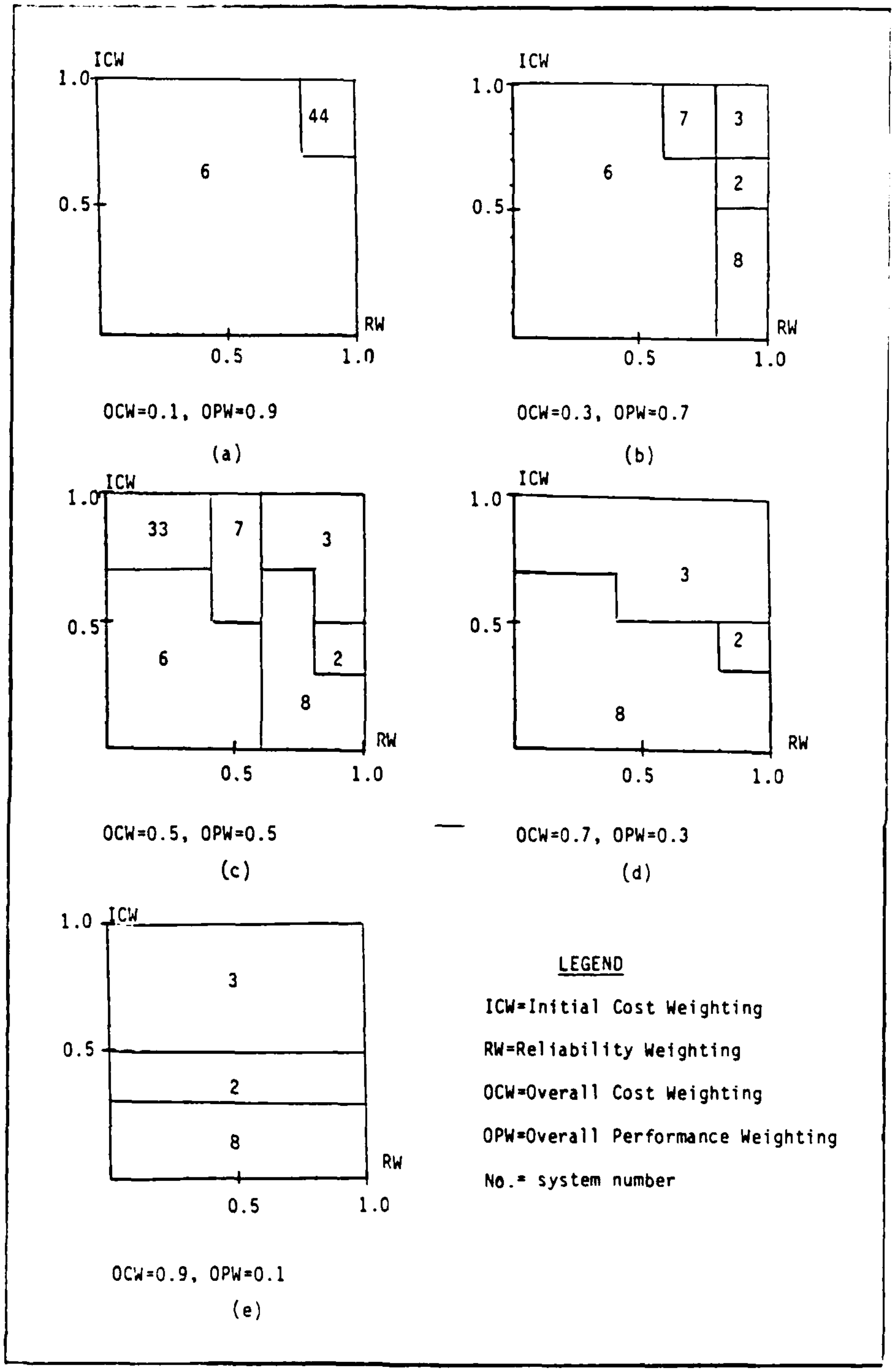

Figure 6.8 Preference Conditions For Systems to Appear in 'Top' Position

If a decision maker were trying to "sell" his choice of system to a group with many diverse preferences, he might be interested in a system which appeared in the number one position over the widest range of values. Alternatively he may choose to select a system which stays within the top five positions over the largest range of weightings. Before selecting a system, it is suggested that the decision maker examine the systems which fall below the "top-ranked" position, to determine if other solutions may be more robust. Since the attributes in the NDSS describe the level of objective attainment, the decision maker can determine the "cost" of selecting a lower-ranked system by referencing the NDSS. The lower-ranked system is still an optimal performer from an engineering viewpoint, but it does not necessarily yield the best potential for the objectives preferred by the decision maker. However, because of its robustness, it may be a better system to implement.

Consider another example, where upon performing sensitivity and obtaining the results, the analyst found that the system within the number one position would change for slight variations in the decision maker's preferences. The analyst should inform the decision maker that the system in the "top" position remains there only under stringent preference conditions. For instance, consider system 44 in this study. It is the "top" choice for preference weightings of overall cost=0.1, initial cost=0.8, and reliabil-

ity=0.9. Yet, if the preferences of the decision maker were to change slightly, that choice would be eliminated from the number one position. The decision maker needs to be informed that he might wish to alter his preferences to select a system which meets a wider range of values.

6.3.4 Systems Within Top Five and Ten Positions. Generally a decision maker would pick the highest-ranked solution (i.e. system). However, there may be cases where it is more beneficial to choose a system within the top 5 or 10 system positions. Again, it might be necessary to satisfy a very wide range of preferences. This may lead the decision maker to choose a system within the "top" five positions because it appears in the ranking over the necessary range of preferences that he needs. If the systems appearing in the number one position do not meet the decision maker's requirements for robustness, a system within the top 5 or 10 positions would be the next best choice. Table 6.13 shows the relative frequency of occurrence over the range of weightings tested for each of the systems within the top 5 positions. System 9, for example, represents a system that occurs in the top 5 positions frequently, but that never appears in the "top-ranked" spot. Figure 6.9 provides a physical description of system 9.

Similarly, Table 6.14 lists the relative frequency each system falls within the top 10 positions over the range of weightings tested.

Table 6.13

Systems Ranked in Top Five Positions

System #	# Times in Top 5	% Time in Top 5	System #	# Times in Top 5	% Time in Top 5	System #	# Times in Top 5	% Time in Top 5
1	5	6.25	24	0	0.00	47	0	0.00
2	42	52.50	25	11	13.75	48	0	0.00
3	35	43.75	26	9	11.25	49	0	0.00
4	4	5.00	27	0	0.00	50	0	0.00
5	2	2.50	28	0	0.00	51	0	0.00
6	32	40.00	29	0	0.00	52	19	23.75
7	25	31.25	30	0	0.00	53	19	23.75
8	48	60.00	31	0	0.00	54	0	0.00
9	45	56.25	32	0	0.00	55	0	0.00
10	12	15.00	33	6	7.50	56	0	0.00
11	4	5.00	34	0	0.00	57	0	0.00
12	5	6.25	35	0	0.00	58	0	0.00
13	0	0.00	36	0	0.00	59	0	0.00
14	0	0.00	37	0	0.00	60	0	0.00
15	0	0.00	38	0	0.00	61	0	0.00
16	0	0.00	39	0	0.00	62	0	0.00
17	0	0.00	40	0	0.00	63	0	0.00
18	0	0.00	41	0	0.00	64	0	0.00
19	0	0.00	42	0	0.00	65	0	0.00
20	0	0.00	43	2	2.50	66	0	0.00
21	0	0.00	44	31	38.75	67	0	0.00
22	13	16.25	45	31	38.75	68	0	0.00
23	0	0.00	46	0	0.00	69	0	0.00

Note-Figures taken from a total of 80 runs with varied weightings.

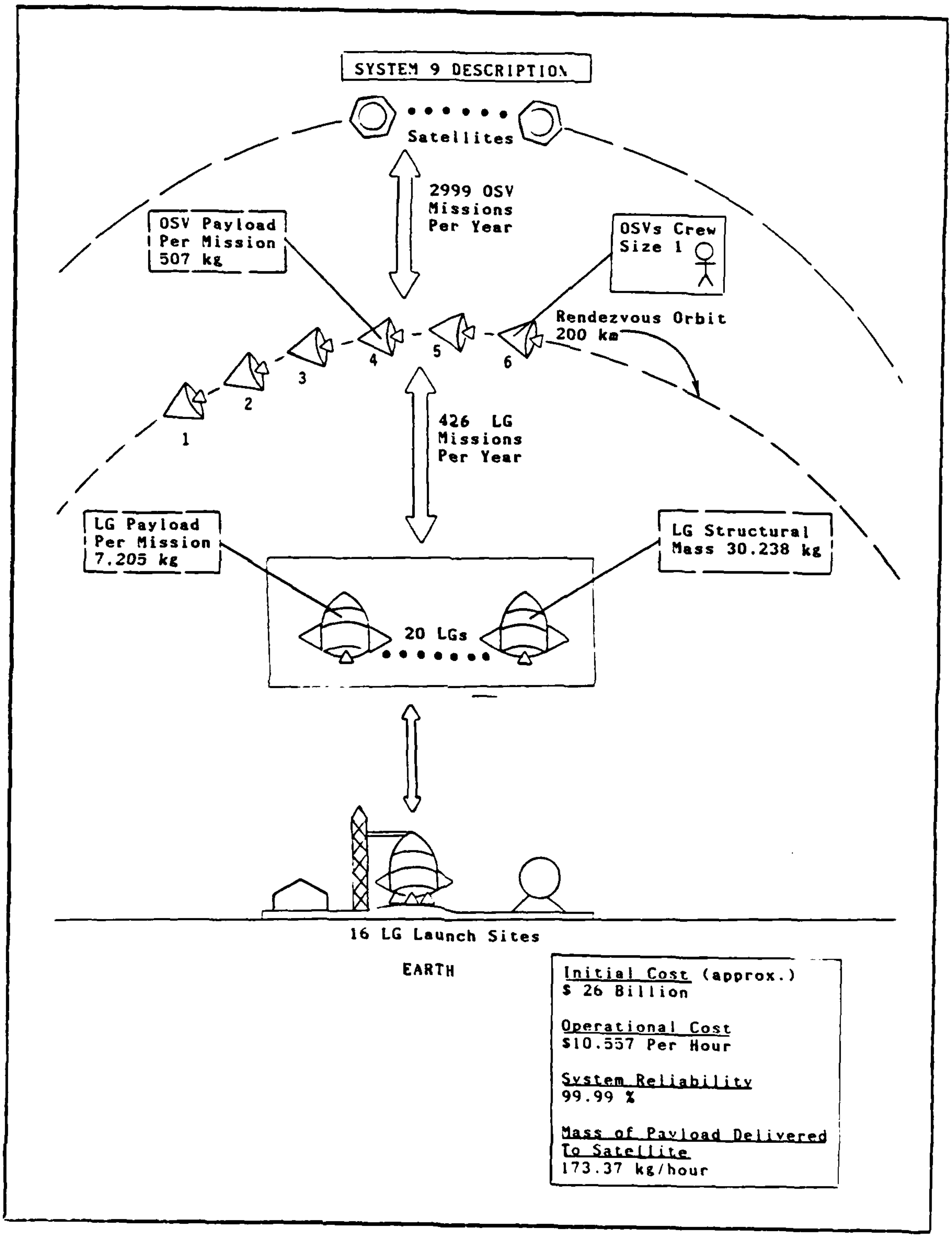

Figure 6.9 Physical Description of System 9

Table 6.14

Systems Ranked in Top Ten Positions

System #	# Times in Top 10	% Time in Top 10	System #	# Times in Top 10	% Time in Top 10	System #	# Times in Top 10	% Time in Top 10
1	29	36.25	24	35	43.75	47	0	0.00
2	46	57.50	25	45	56.25	48	0	0.00
3	44	55.00	26	42	52.50	49	0	0.00
4	13	16.25	27	18	18.75	50	0	0.00
5	6	7.50	28	12	15.00	51	0	0.00
6	32	40.00	29	9	11.25	52	27	33.75
7	48	60.00	30	6	7.50	53	27	33.75
8	51	63.75	31	0	0.00	54	11	13.75
9	49	61.25	32	0	0.00	55	4	5.00
10	31	38.75	33	20	25.00	56	0	0.00
11	18	22.50	34	0	0.00	57	0	0.00
12	16	20.00	35	0	0.00	58	0	0.00
13	0	0.00	36	0	0.00	59	0	0.00
14	8	10.00	37	0	0.00	60	0	0.00
15	17	21.25	38	0	0.00	61	0	0.00
16	0	0.00	39	5	6.25	62	0	0.00
17	3	3.75	40	5	6.25	63	3	3.75
18	0	0.00	41	2	2.50	64	5	6.25
19	2	2.50	42	0	0.00	65	2	2.50
20	0	0.00	43	7	8.75	66	0	0.00
21	3	3.75	44	31	38.75	67	1	1.25
22	31	38.75	45	34	42.50	68	0	0.00
23	5	6.25	46	0	0.00	69	0	0.00

Note-Figures taken from a total of 80 runs with varied weightings.

6.4 Summary. Designing a value system allows an analyst to capture the preferences of a decision maker in an efficient and repeatable manner. Once the analyst has determined the decision maker's preferences, the analyst creates a weighted hierarchy of objectives from which a scalar figure of merit can be calculated for each system. The most desirable solution is usually the system with the largest associated figure of merit. However, it is important to know how sensitive a particular solution is to changes in the decision maker's preferences.

Sensitivity analysis involves determining how sensitive a system's ranked position is to changes in the decision maker's preferences. This requires examining system ordering characteristics as the weightings are varied. Ideally, system rankings for all possible combinations of varied weightings could be generated to determine the robustness of the solution rankings. Typically, though, generating all possible combinations of all possible weighting values is a prohibitively large task. Steps can be taken to identify which weightings significantly produce system ordering variations. By examining "sub-figure of merit" results at the lowest level of the hierarchy tree of objectives, these "significant" weights may be found. These "significant" weighting values can then be used to represent those weighting values not used, to calculate overall figures of merit. Although some bias of system ordering may be introduced for

those weighting values not actually used in the figure of merit calculations, making reasonable assumptions from the "sub-figure of merit" results can minimize the biases, and produce useful information for the decision maker.

Using the sensitivity analysis techniques demonstrated in this chapter permits a rigorous examination of possible solutions by the decision maker. Decisions concerning the selection of a "best" solution are now made using quantifiable measures. The value system framework not only provides a way to structure and organize subjective judgements, but it also produces written documentation showing why a particular decision was made.

VII. Conclusions and Recommendations

7.1 Introduction

In the preceding chapters a two-phase approach for designing a complex system was presented and applied to the selection of a satellite servicing system. Detailed analysis was performed on one system alternative composed of a low-G launcher and an orbital servicing vehicle (LG+OSV). Based on these results, the following conclusions and recommendations are made.

7.2 Conclusions

The two-phase approach is a useful method for solving complex problems, as shown in this study. It provides separation of the volatile decision making phase from the expensive, time-intensive engineering design phase. The engineering design phase generates an optimal set of design alternatives. This allows the decision maker to explicitly evaluate tradeoffs among the conflicting objectives without requiring a completely new engineering analysis for each tradeoff.

This methodology was used to generate an NDSS for a LG+OSV servicing system. Use of a value system representing decision maker preferences enabled a ranking of the alternative configurations for this servicing system. It was found to be time-efficient to begin design of the value system

immediately following the problem definition step, and prior to the system modeling. This allows the same objectives and attributes to be established for both the first and second phases of the approach.

For the LG+OSV model, it was found using value system sensitivity analysis techniques that system designs 2, 3, 6, 8, and 9 remained highly ranked over a wide range of decision maker preferences. The design variables for systems 2 and 3 all have values within the valid range of the model at the current level of detail. Some of the design variables for systems 6, 8, and 9 are beyond the valid range of the model for this level of detail.

System 2 would be selected if a decision maker preferred a system to have a high measure of reliability, but made little distinction in his preferences between minimizing operational versus initial costs. Figure 7.1 helps one visualize the conditions necessary for system 2 to be ranked in the "top" position. Figure 7.2 provides a physical description of system 2.

System 3 would be selected if a decision maker preferred a system that minimized initial system costs, and also emphasized minimizing the overall system cost. Again Figure 7.1 helps one visualize the conditions necessary for system 3 to be selected as the "top" system. Figure 7.3 provides a physical description of system 3.

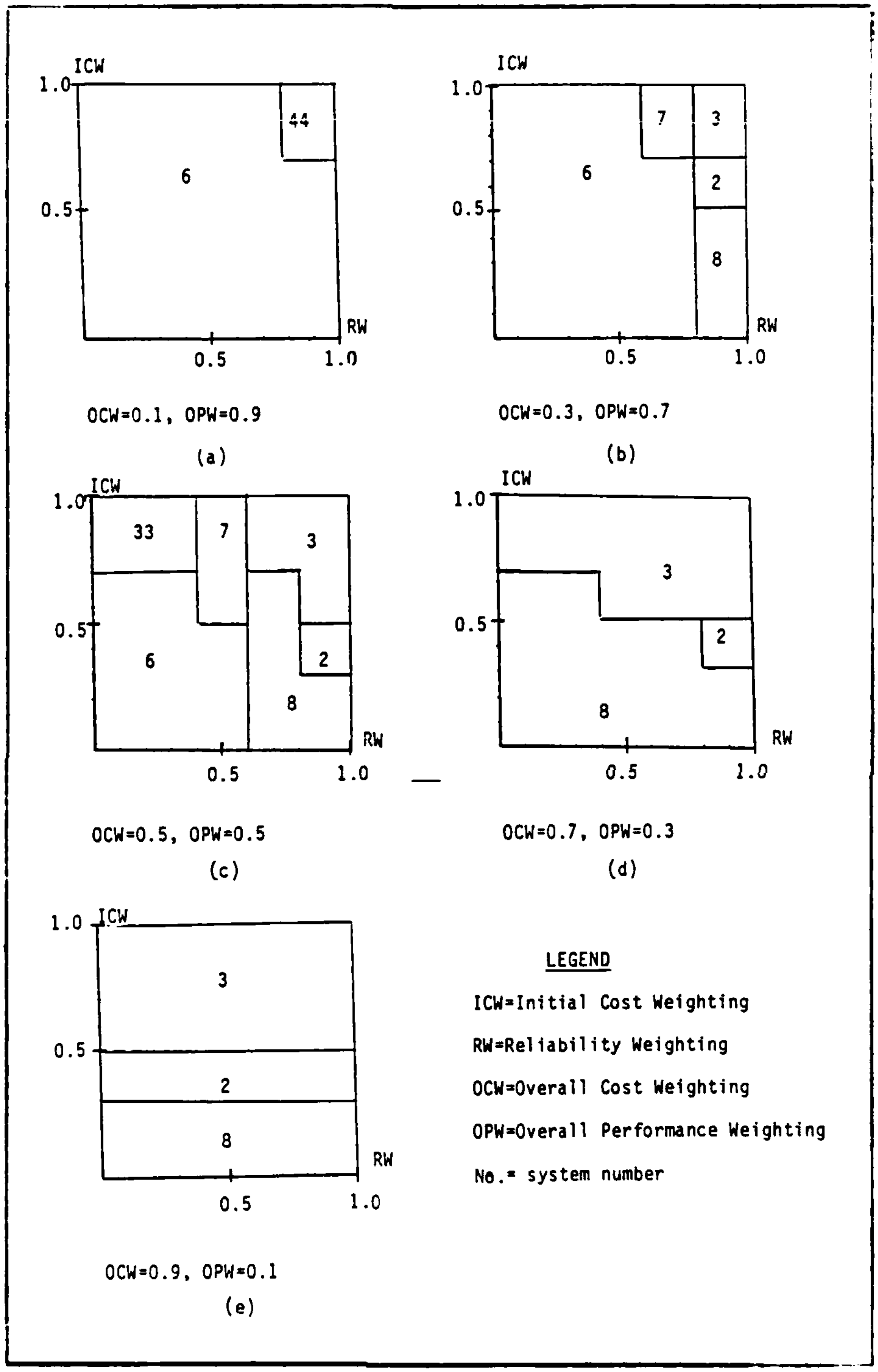

Figure 7.1 Preference Conditions For Systems to Appear in 'Top' Position

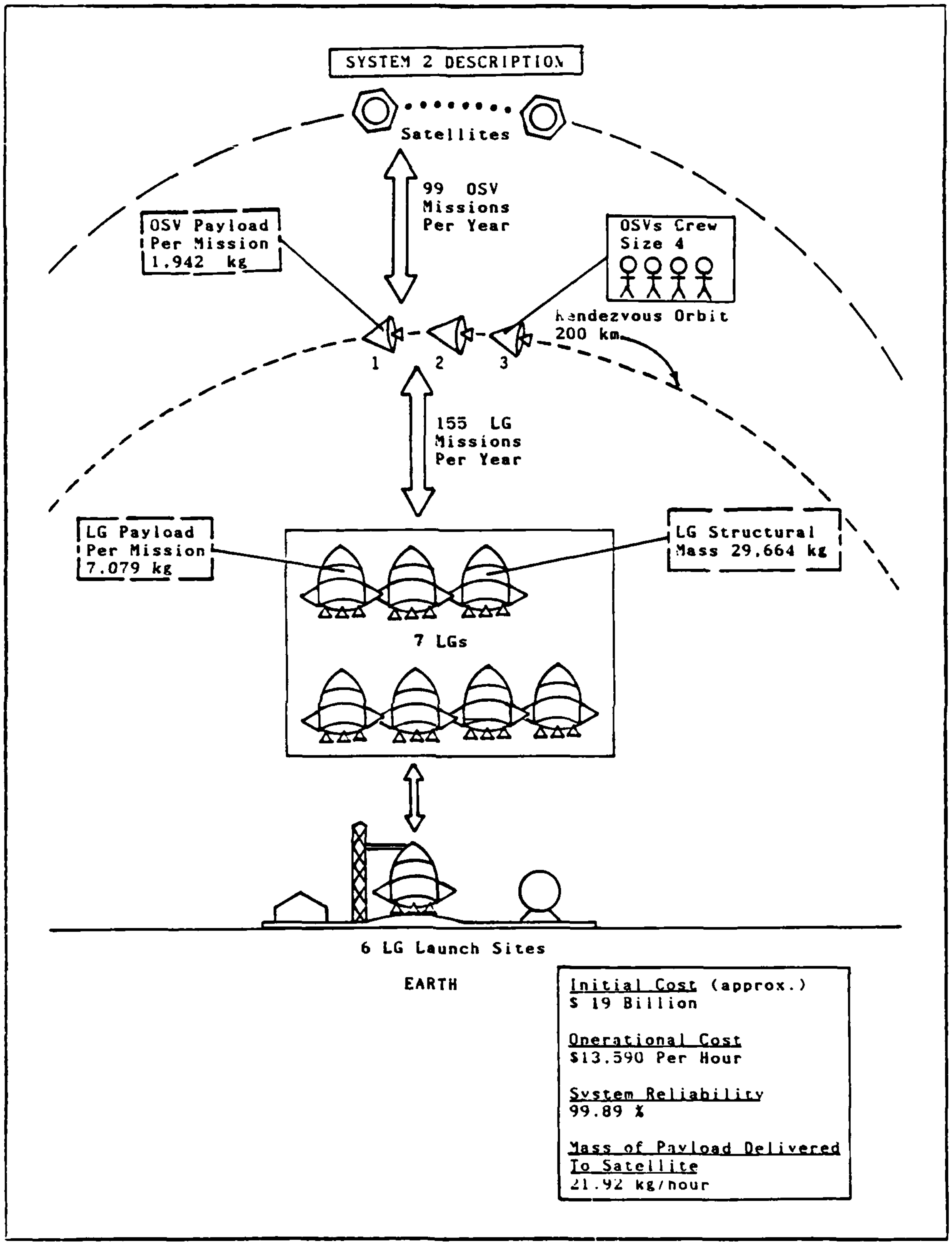

Figure 7.2 Physical Description of System 2

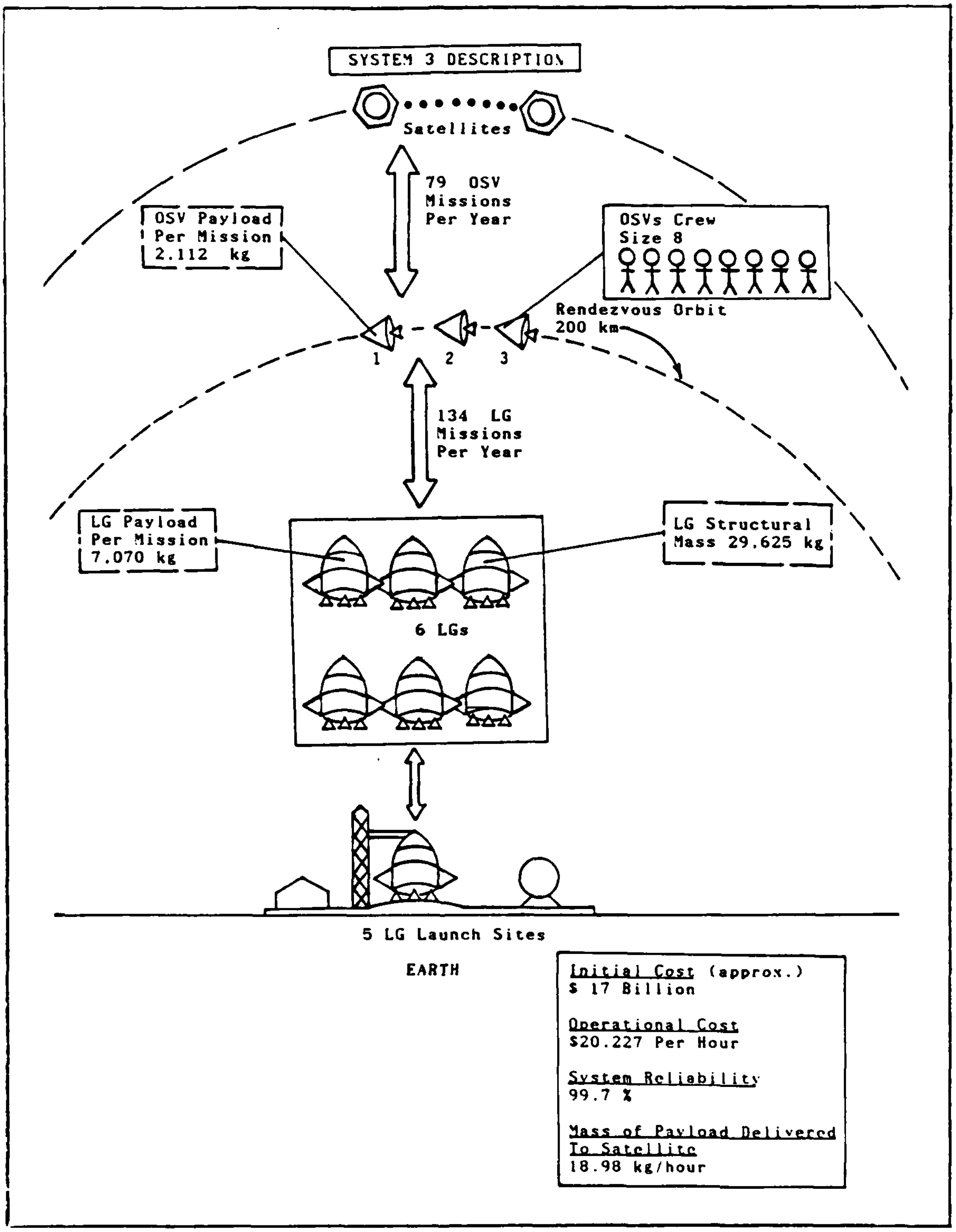

Figure 7.3 Physical Description of System 3

Systems 6, 8, and 9 all have state variables (described in Chapter V) which take on values which are beyond the valid ranges of the model. Though they appeared in the highly ranked positions under the conditions of Table 6.13, and Tables 6.7 to 6.11, they are invalid designs and should not be used as the basis for further work, until the model is refined to correct the problems identified in Chapter V.

7.3 Recommendations

For further refinements to the value system phase of designing a satellite servicing system, the following recommendations should be considered.

1. Use the Detailed Hierarchy of Objectives for Selection of a Satellite Servicing System as described in Appendix B to include more of the concerns involved in this complex problem. Preferences should then be solicited from the decision maker based on the new objectives and new attributes, and new system rankings can then be determined based on this detailed hierarchy.

2. For a more detailed analysis, don't assume a linear value function. Solicit preferences from decision makers who would be involved in such a system selection to determine if non-linear value functions are more descriptive. It is possible that more of some performance measure may have more value to a decision maker only up to a point. Past that point the value of more performance may actually decrease. This non-monotonic value function could possibly be modeled as a linear combination of the suggested value function forms described in Section 3.4.2. These types of conditions need closer examination.

3. Sensitivity analysis on the value system using a Monte Carlo technique will eliminate possible biasing of results. For a large number of trials (possibly 1000-10000), use a random number generator to produce preference weightings. These preference weightings can then be used with the decision maker's "values" from the value functions to determine the sensitivity characteristics described in Chapter VI. Note,

however, to understand the conditions causing systems to be "top-ranked", each different preference weighting must be recorded and related to the system ranking it produced.

Future iterations in the modeling step should consider the following refinements to the model.

1. Use the Detailed Hierarchy of Objectives for Selection of a Satellite Servicing System as described in Appendix B in the modeling phase for generating performance measures for these more detailed objectives.

2. The state variable for number of satellites serviced per OSV mission (X560) invalidates the equation for determining OSV fuel requirements (Eq (D.22)) when it has a value less than one. However, in equations involving things such as mass needed or mass delivered (Eqs (D.23),(D.24),(D.26), and (D.28)), it is desirable to allow this variable to have values less than one. Setting X560 equal to a value of one only in Eq (D.22), when it actually has a value less than one, will produce the desired results in the model and eliminate inconsistencies.

3. Refine the equations that define the life support requirements for the OSV, or limit the crew size to the model range of applicability of less than 20 people.

4. Refine the relations that represent the tradeoffs between performing the servicing with higher levels of automation (unmanned) versus manned techniques.

5. The current model only examines relative costs for comparative purposes, and does not yield total costs for the systems (see Chapter IV). Improve the cost estimating equations to allow their use to predict total versus relative costs.

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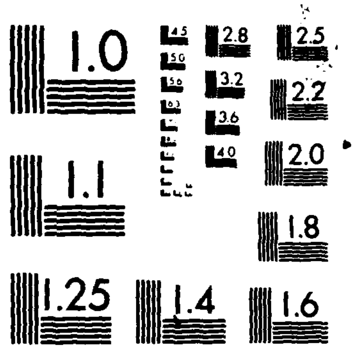
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VOLUME II - FINAL REPORT

A two-phase methodology for selecting an optimal military satellite servicing system is developed using the systems engineering approach. This methodology is used to evaluate several alternative systems at varying levels of detail. The candidate systems are composed of low-G launchers, high-G launchers, orbital servicing vehicles, and space bases. An optimal realization is then derived for a system of low-G launchers and orbital servicing vehicles. In the first phase of the approach, vector optimization techniques are used to vary the states of a model to obtain a set of optimal solutions. The second phase embodies the decision maker's preferences in a value system to enable preference ranking of the optimal solutions in the non-dominated solution set. This methodology, as presented, can be applied to any complex problem with multiple conflicting objectives. It is designed for use by an engineering organization supporting a senior-level decision maker.

The report is in three volumes. The Executive Summary (Volume I) is a cursory review of the study and is meant to be self-contained. The Final Report (Volume II) and the Appendices (Volume III) are more detailed and should be read together for completeness.

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